CLOSED LOOP SYSTEMS IN MECHANICAL VENTILATION

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Points to be covered

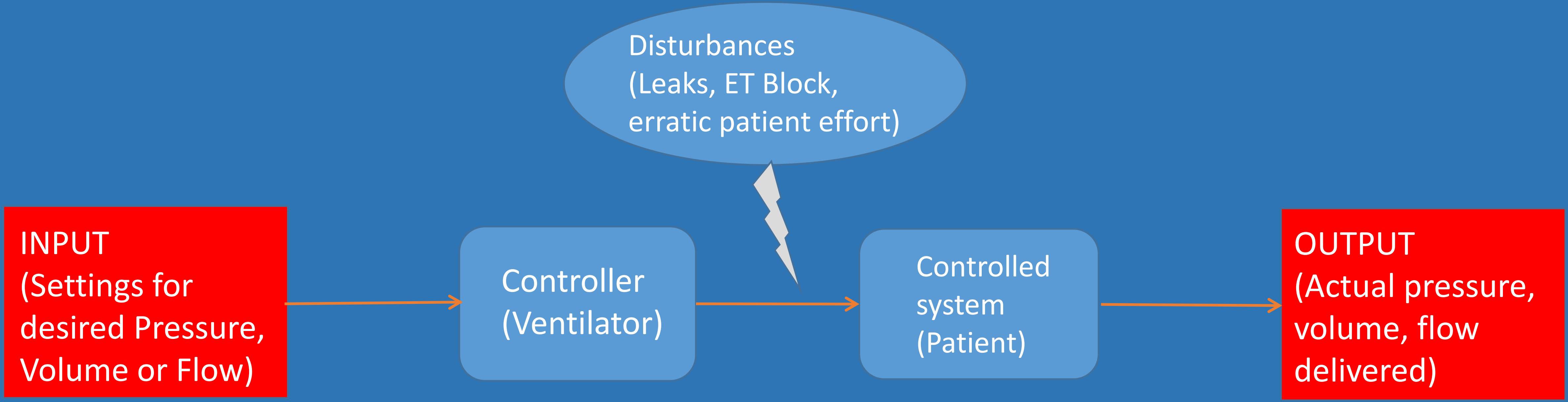
- Introduction
- Advantages of Closed Loop systems
- Prerequisites
- Description of Various Modes
- Do they translate into clinical benefit?
- Conclusions

What are closed loop systems?

Types of Ventilator Control systems

1. Open Loop system
2. Closed Loop system (feedback control system)

Open Loop system



Open Loop system

- Simple, cheap and *stable* System…

BUT

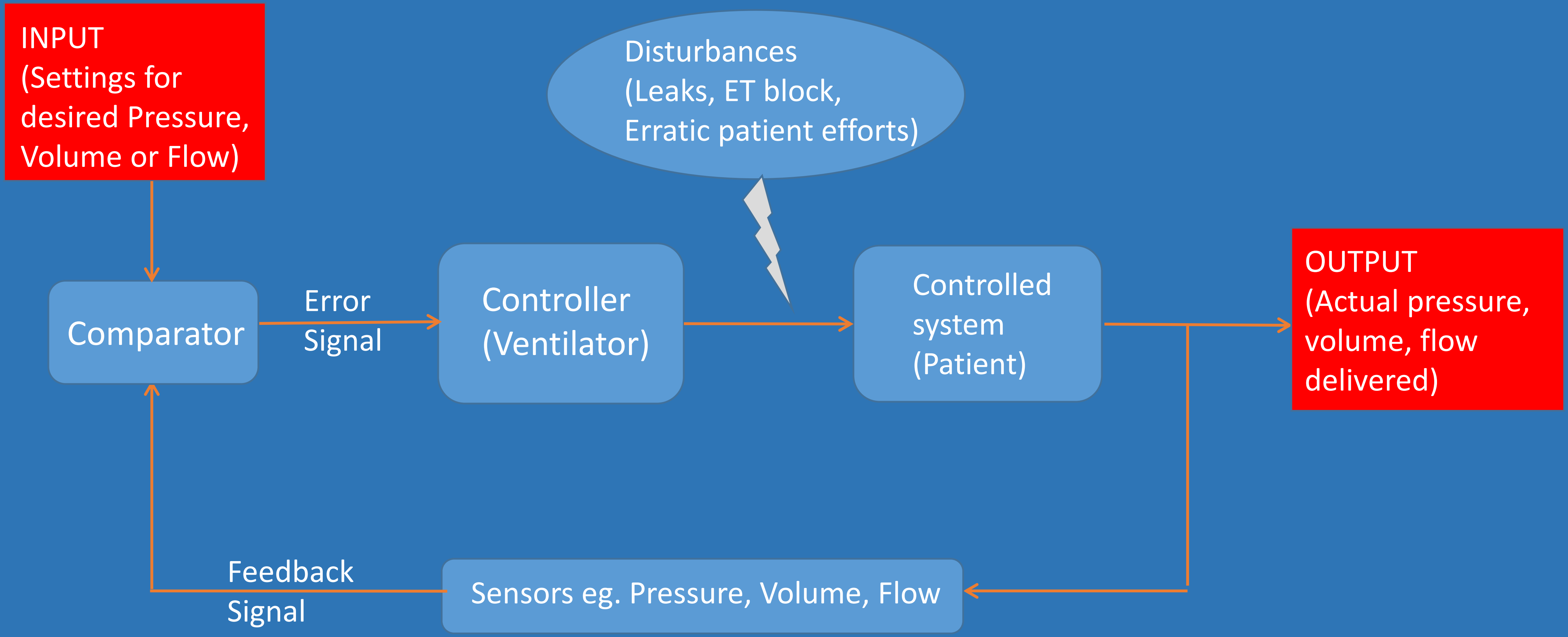
- No feedback from patient to compare with desired settings
- Hence cannot take into account disturbances
- Cannot correct its own output → Has to be changed manually
- Eg. Conventional modes – ACMV (PCV/VCV), PSV, SIMV

Closed Loop system

- A system where the measured output has an effect upon the input quantity in such a manner as to maintain the desired output

- Loop becomes closed by introducing
  a) Sensors for various parameters
  b) Feedback pathway
  c) Comparator

Closed Loop system



Comparison with Open Loop Systems

Open Loop

- All settings need to be set manually
- Output needs to be monitored frequently and settings changed accordingly
- Cheap, simple, stable
- Asynchrony

Closed Loop

- Some settings are automatically adjusted as per monitored parameters
- Takes into account disturbances too and makes corrective action
- Sophisticated and hence costly
- Better synchrony

What parameters to close the loop?

- Accurate
- Reproducible
- Technology integrated in ventilator
- Not very expensive
- Non-invasive

What parameters to close the loop?

A. Patient effort – Respiratory muscle support
   - Flow, Resp Rate, Diaphragmatic EMG

B. Ventilation
   - Expiratory time constant, $ETCO_2$

C. Oxygenation
   - SpO_2

Anticipated Benefits

- Rapidly adapts ventilation to the lung condition – more physiological
- Increases safety
- Better ventilator-patient synchrony
- More patient comfort, less need for sedation/paralysis
- Decreases weaning duration
- Decreases workload on doctors, nurses
- Liberates clinicians from simple tasks → Can concetrate on complex time consuming patients
- Decreases false alarms..

Classification based on Levels of autonomy (and complexity!)

1. Manual – All targets set manually – No autonomy to ventilator
   Eg. ACMV, PSV, PCV, SIMV

✡ 2. Servo control – Target changes depending on patient effort
   Eg. ATC, PAV, NAVA

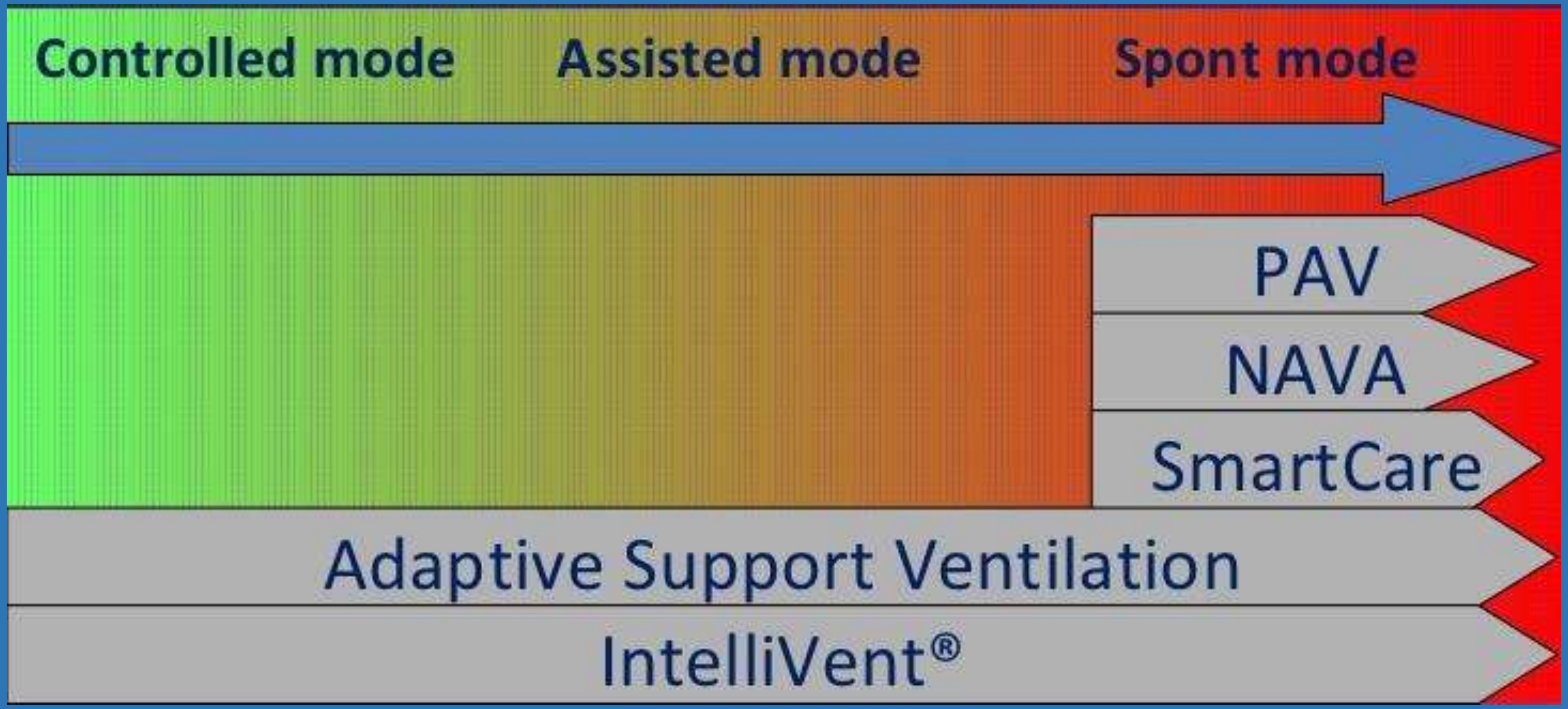
✡ 3. Automatic Control – Ventilator decides targets based on mathematical models or Artificial Intelligence
   Eg. MMV, ASV, SmartCare, Volume Support

✡ Closed Loop Systems

Modes – according to level of autonomy

Manufacturer's Mode Name	Autonomy
Volume Control Ventilation Assist/Control	Manual
Pressure Control	Manual
Synchronized Intermittent Mandatory Ventilation	Manual
Pressure Controlled Synchronized Mandatory Ventilation	Manual
Spontaneous/Timed Ventilation	Manual
Pressure Support Ventilation	Manual
Intermittent Positive Pressure Ventilation With Pressure Limited Ventilation	Manual
Volume Control	Manual
Volume Control Assist Control With Machine Volume	Manual
Synchronized Intermittent Mandatory Ventilation With Pressure Limited Ventilation	Manual
Synchronized Intermittent Mandatory Ventilation With Machine Volume	Manual
Automatic Tube Compensation	Servo
Proportional Assist Ventilation Plus	Servo
Proportional Pressure Support	Servo
Neurally Adjusted Ventilatory Assist	Servo
Assist/Control (Adaptive Flow and I-Time)	Automatic
Pressure Regulated Volume Control	Automatic
Volume Controlled Synchronized Mandatory Ventilation (Adaptive Flow and I-Time)	Automatic
Mandatory Minute Volume Ventilation	Automatic
AutoMode (PRVC - VS)	Automatic
Volume Support	Automatic
Mandatory Rate Ventilation	Automatic
Adaptive Support Ventilation	Automatic
SmartCare/PS	Automatic

Common Commercially available modes



Servo Modes

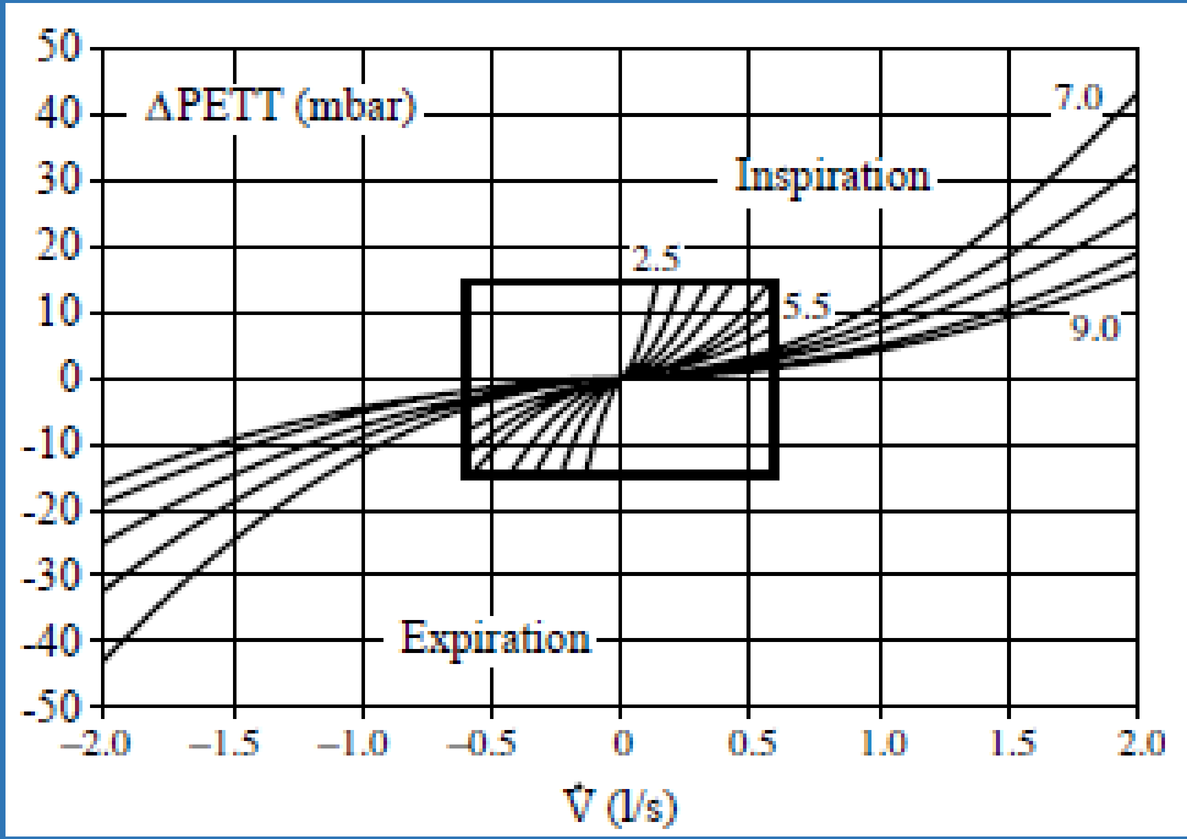
- Term “servo” coined by Joseph Farcot in 1873 to describe steam-powered steering systems.
- Later, hydraulic “servos” were used to position anti-aircraft guns on warships.
- Servo control converts a small mechanical motion into one requiring much greater power, using a feedback mechanism.
- Similar to “Power Steering” in Cars!
- High level of patient ventilator synchrony
- Ventilator output closely matches patient demand

Automatic Tube Compensation (ATC)

Principle

- Narrowest part of circuit = ET tube
- Hence there is a pressure drop across ET = ΔP
- This amount of pressure required to overcome ET resistance
- ET resistance not constant → Proportional to Flow
- Hence ΔP too not constant → Proportional to Flow generated by patient (i.e. Patient demand)
- Patient demand and flow rate varies breath by breath and patient to patient

Pressure~Flow relationship in ET tube



Pressure

Flow

Conventional PSV (without ATC)

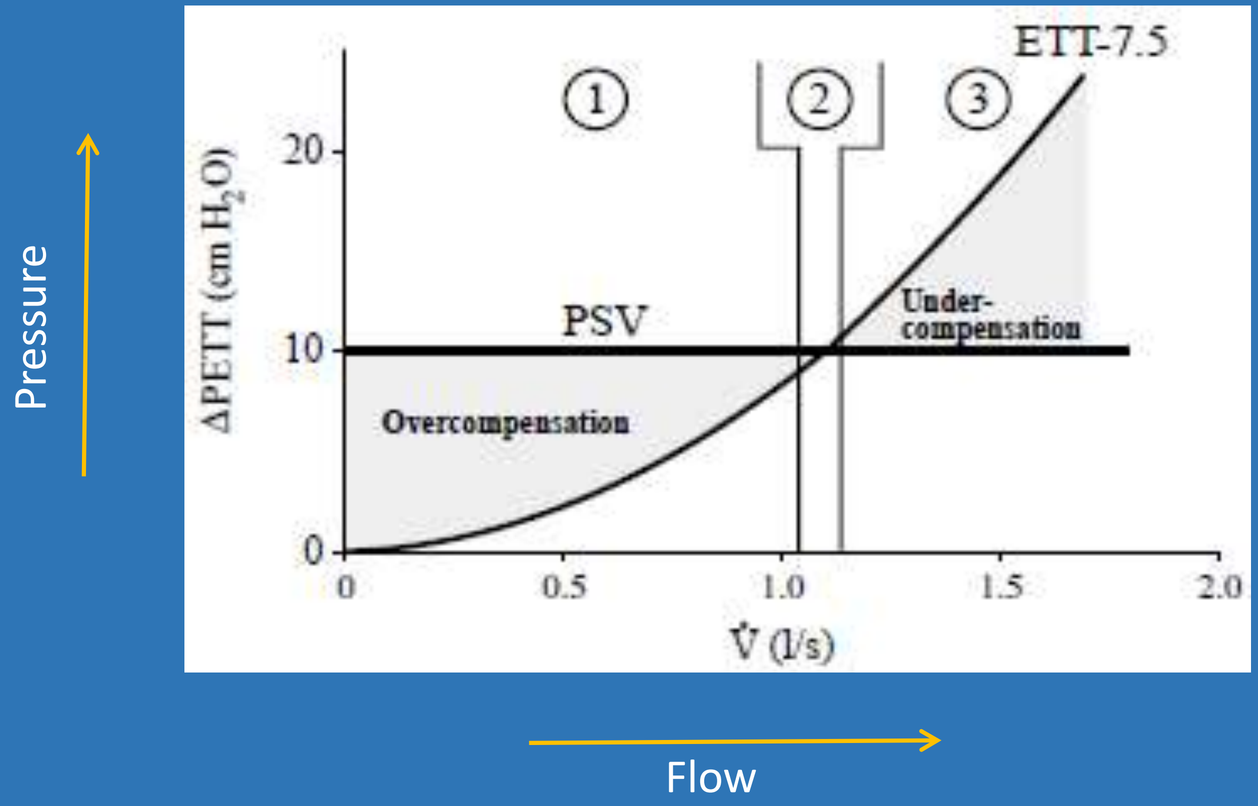
- In PSV without ATC → Regardless of patient demand → Same Pressure applied (IPAP) to each breath
- However we don't know what portion of pressure applied is lost in overcoming tube resistance
- 3 scenarios arise:

1) at low flow rates, PSV overcompensates for tube resistance

2) at medium flow rates, PSV compensates for tube resistance

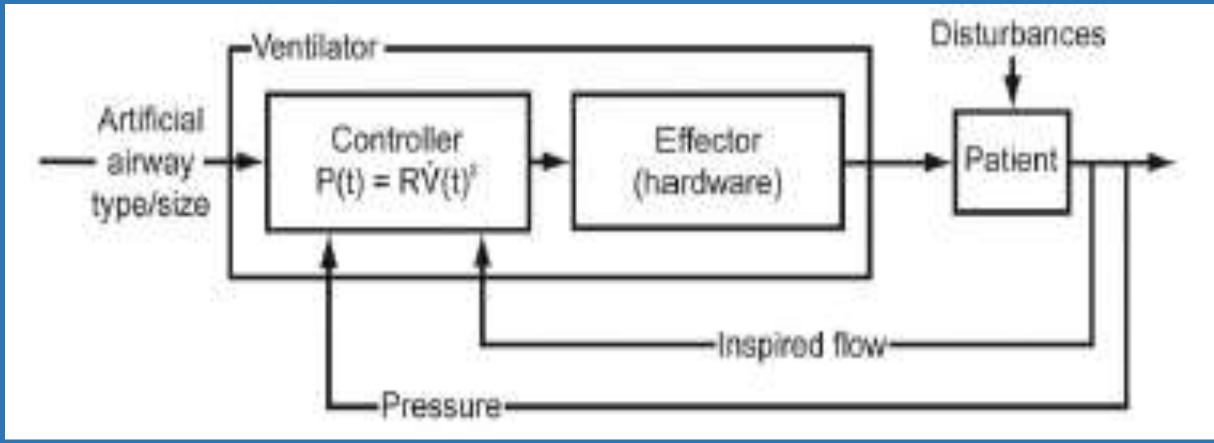
3) at high flow rates, PSV undercompensates for tube resistance

Conventional PSV (without ATC)



ATC

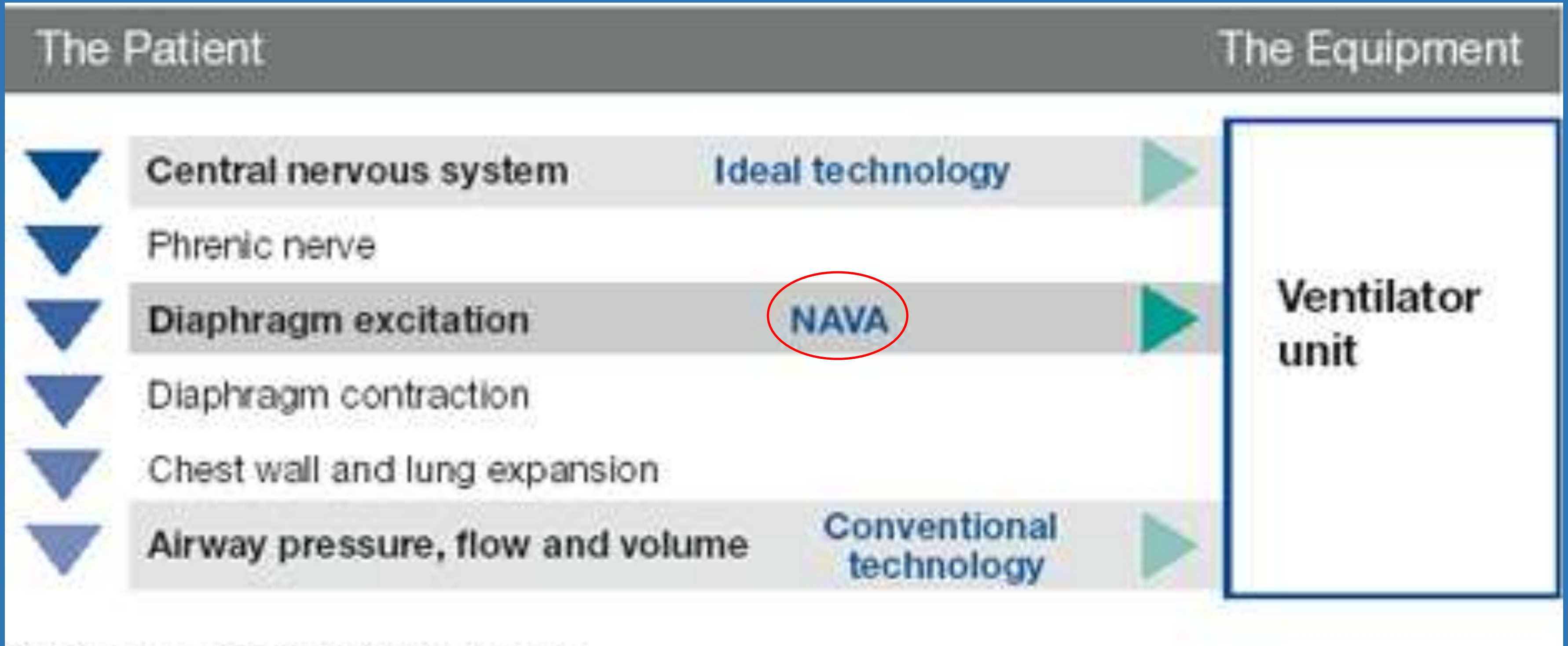
- Analyses the flow across ET during each instant and decides Pressure Compensation based on the curve
- Hence ATC → Non-linear flow dependent Pressure Support
- Present in:
  - Drager Evita 4 and XL, Viasys Avea, Hamilton Galileo
- Inputs required
  - Type of tube (ET vs tracheostomy)
  - Inner diameter of tube
  - % compensation required (0-100%)



Clinical Benefit? - Controversial

- Basically → Alternate weaning strategy
- Theoretically decreases WoB and gives better patient comfort
- Failure of SBT in ATC mode compared to PSV may have better predictive value for extubation failure (NPV 83% vs 56%)
- May shorten weaning process in children
- However several RCTs in adults failed to show it is better than PSV/T-piece in shortening weaning, or better predicting succesful weaning.

Neurally Adjusted Ventilatory Assist (NAVA)



Sinderby C et al. Nat Med 1999;5(12):1433-1436.

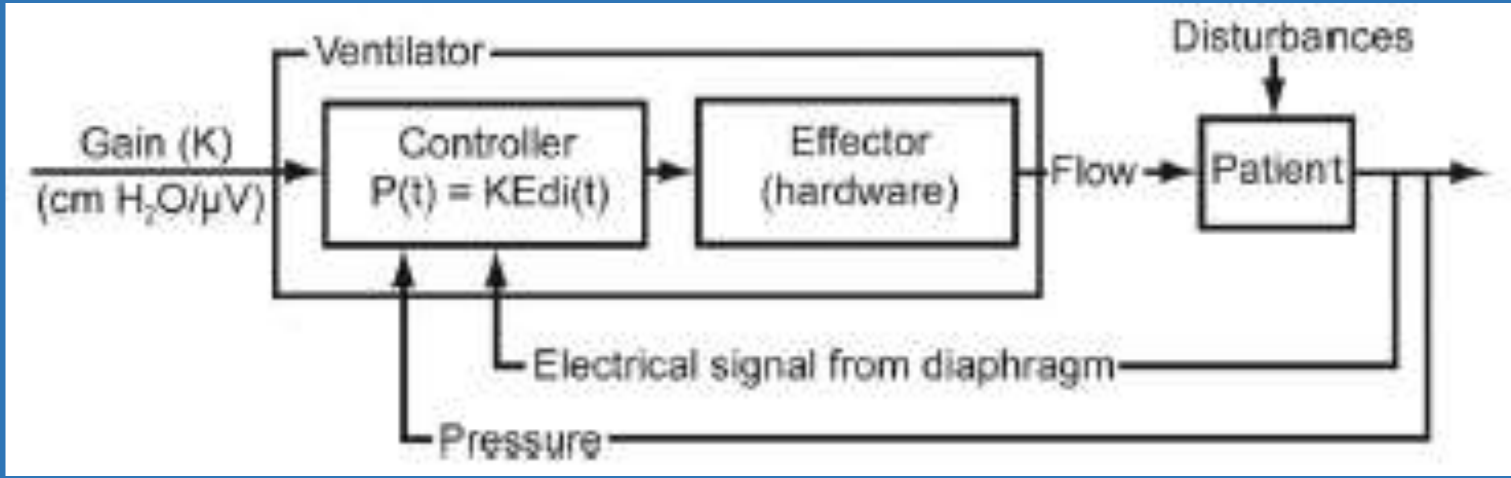
NAVA

- Developed by Maquet in 2006, available only in Servo
- Esophageal catheter with electrodes placed to record diaphragmatic EMG (Edi)
- EMG signal is amplified into inspiratory Paw
- Amount of amplification decided by gain factor - “NAVA level”

$$Ppeak = NAVA\ level \times (Edi_{peak} - Edi_{min}) + PEEP$$

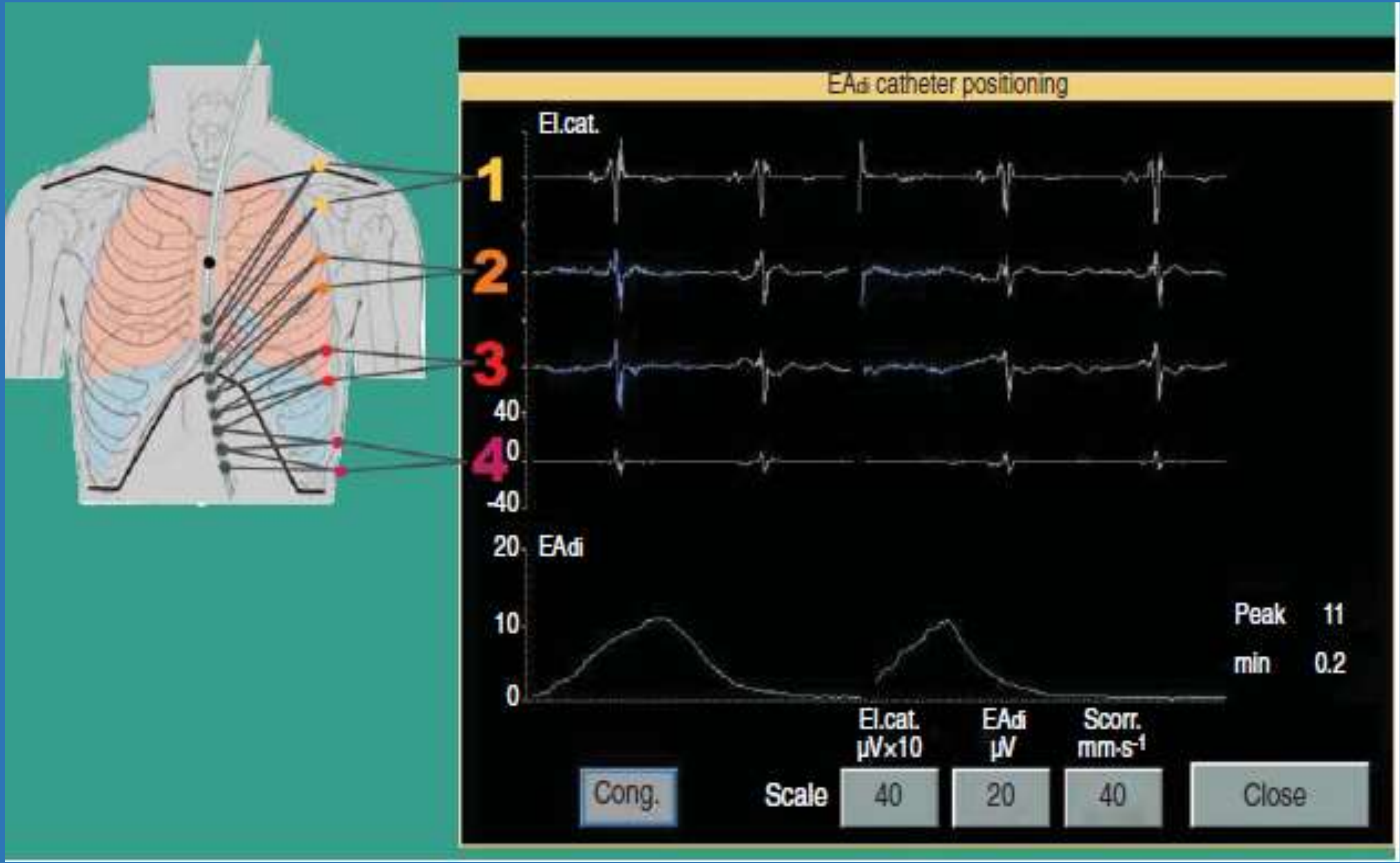
- Set by clinician based on patient’s ventilatory demand
- Hence main principles of NAVA:
  a. Triggering is at diaphragmatic level
  b. Pressure support during each breath proportional to EMG signal

NAVA – Schematic Diagram



EMG (uV)

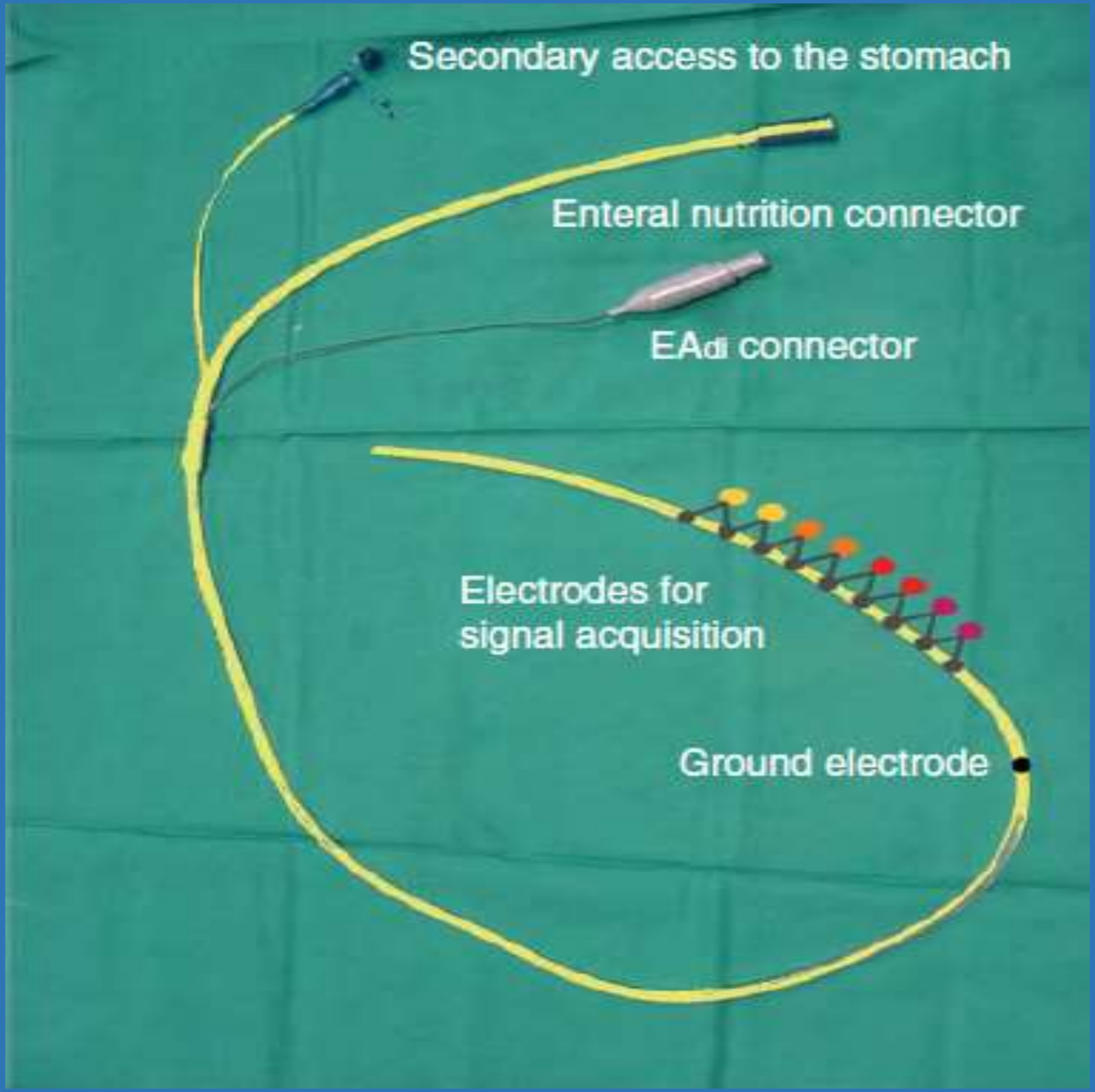
Gain Factor (cmH20/uV)



EAdi catheter positioning
El.cat.
1
2
3
4
40
0
-40
20
EAdi
10
0
Peak 11
min 0.2
El.cat. µV×10
EAdi µV
Scorr. mm·s-1
Cong.
Scale
40
20
40
Close

Insertion of Esophageal Catheter

- Similar to NG tube – In fact esophageal catheter acts as feeding tube
- Size 6 Fr – 16 Fr (usually 16F, 125 cm length for adults)
- Insertion length according to formula provided in catheter package
- Test Edi Module and Connect Edi Cable to Edi Catheter
- Check catheter position: using ECG waveform from the electrodes in the catheter
- Fix like Ryle’s tube


Secondary access to the stomach
Enteral nutrition connector
EAdi connector
Electrodes for
signal acquisition
Ground electrode

Setting NAVA level

- Put patient in conventional mode (PSV/PCV), Select “NAVA preview”
- Two pressure curves appear
  - Yellow, represents the actual pressure delivery
  - Gray, provides estimation of pressure delivered (based on actual Edi and NAVA level) if patient were switched to NAVA at this time
- Adapt NAVA level so that area under the estimated pressure curve (gray) resembles area under the actual pressure curve (yellow)
- Usual level is 0.5 to 3 cmH2O/uV
- Weaning → Reduce by 0.2 cmH2O/uV at a time

Authors	Group	Study design	Duration	Outcome
Colombo and colleagues, 2008	Acute respiratory failure(n = 14)	Crossover study – NAVA vs PSV set to obtain VT 6 to 8 ml/kg	20 minutes x 3	NAVA averted the risk of overassistance and improved synchrony
Wu and colleagues, 2009	ARDS (n = 18)	PSV vs. NAVA – randomized study. Incremental PSV and NAVA adjusted in 4 steps	5 minutes x 4	Improved synchrony with NAVA
Brander and colleagues, 2009	Acute respiratory Failure (n = 15)	NAVA level increased progressively and Edi measured for next 3 hrs	3 hours	Progressive implementation of NAVA may be a method for determining the adequate level – downregulation of Eadi Confirmed
Schmidt and colleagues, 2010	Acute lung injury (n = 12)	Longitudinal observational study – NAVA vs. PSV with increasing assist	10 minutes x 4	NAVA increases breathing pattern variability
Coisel and colleagues, 2010	Postop patients (n = 15)	Crossover randomized – NAVA vs. PSV.	24 hours	Variability of, tidal volume and minute ventilation were signifi cantly higher with NAVA than with PSV. Variability of electrical diaphragmatic activity was signifi cantly lower with NAVA than with PSV. Oxygenation increased with NAVA
Terzi and colleagues, 2010	ARDS (n=11)	Crossover randomized – NAVA vs. PSV	5 minutes x 4 x 3 = 60 minutes	Compared with PSV, NAVA limited the risk of overassistance, prevented patient–ventilator asynchrony, and improved overall patient–ventilator interactions. Compared with the pneumatic trigger, NAVA significantly decreased patient–ventilator asynchrony
Spahija and colleagues,2010	COPD (n=14)	Prospective, comparative crossover – NAVA vs PSV	10 minutes x 2	NAVA improved patient–ventilator synchrony by reducing the triggering and cycling delays, especially at higher levels of assist, while preserving breathing and maintaining blood gas exchange
Passath and colleagues, 2010	Unselected patients (n=20)	Longitudinal observational study. Evaluation of effects of PEEP on breathing pattern and neuroventilatory efficiency during NAVA.	20 minutes x 3	During NAVA, increasing PEEP reduces respiratory drive. Patients adapt their neuroventilatory efficiency such that the individual ventilatory pattern is preserved over a wide range of PEEP levels. Monitoring VT/EAdi during PEEP changes allows identification of a PEEP level at which tidal breathing occurs at minimal EAdi cost
Piquilloud and colleagues, 2011	Unselected patients (n = 22; COPD n = 8/22)	Prospective interventional study – three consecutive periods of ventilation: PSV–NAVA–PSV.	20 minutes x 3	NAVA reduces trigger delay, improves expiratory synchrony and reduces total asynchrony events
Roze and colleagues, 2011	Unselected patients (n = 15)	To determine feasibility of daily titration of NAVA level in relation to diaphragmatic electrical activity measured during a PSV SBT	Until extubation	Daily titration of NAVA level with an electrical goal of 60% EAdimaxSBT is feasible and well tolerated

Potential Benefits

- Improved Synchrony
  - Patient comfort - Providing correct amount of assistance required
  - Better sleep
  - Less V/Q mismatch, decreased O2 requirements
- No influence of Auto-PEEP on triggering
- Edi - Unique monitoring tool to assess
  - Respiratory drive
  - Volume requirements
  - Indications for sedation and weaning – Edi amplitude and Ventilatory assistance decrease as patient improves
  - Assess diaphragm atrophy
- Esophageal ECG

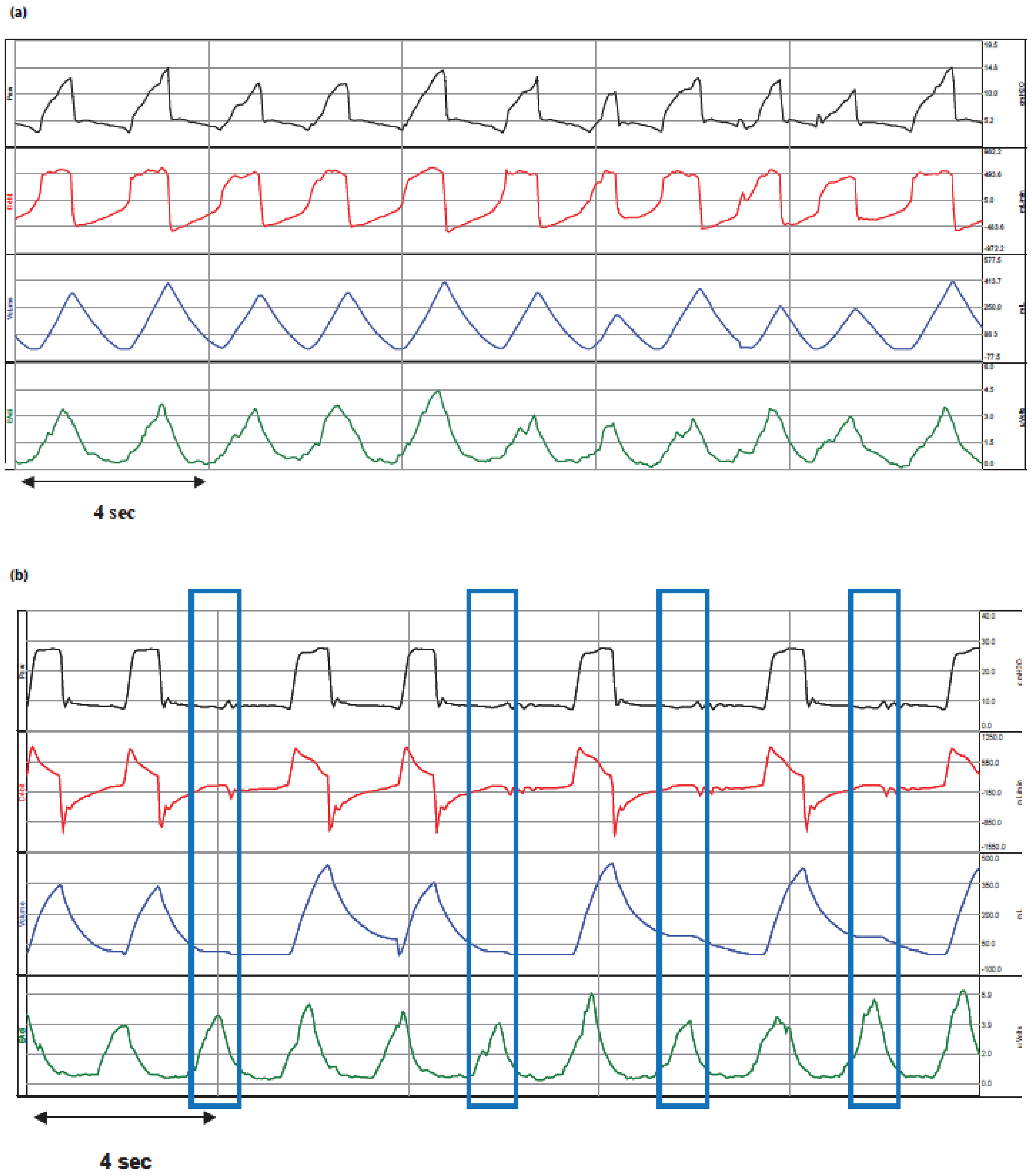


Figure 1. Example of recording during neurally adjusted ventilatory assist and pressure-support ventilation. (a) Neurally adjusted ventilatory assist using the neural trigger: no asynchrony was observed. **(b)** Pressure-support ventilation: wasted efforts are underscored. Each wasted effort is identified by a blue rectangle.

Contraindications

- Known contraindications for naso-/orogastric feeding tube (recent upper airway surgery, esophageal surgery, recent esophageal bleeding, skull base fracture)
- Known phrenic nerve lesions
- Congenital myopathy (relative contraindication)
- MRI scanning: the Edi Catheter not approved for use in MRI environments (Remove from patient before entering MRI area)
- Main Limitations → **INVASIVE, EXPENSIVE**

Does it improve patient outcomes?

- NAVA – Exciting concept given the physiological advantages!
- Whether Physiological benefits translate into better patient outcomes? – Remains to be seen
- As of now, no studies comparing mortality, morbidity and duration of ICU stay

Proportional Assist Ventilation

- First described in 1992 by Younes et al
- Available in Drager Evita XL, Puritan Bennett 840
- PAV is a form of PSV, in which inspiratory airway pressure (Pinsp) within each breath is titrated by the ventilator in proportion to the patient's inspiratory airflow, which is used as a surrogate of the patient's respiratory muscle effort
- Level of amplification decided by:
    a. Lung mechanics – Resistance/compliance
    b. Chosen level of assistance (0-100%)

PAV – Schematic Diagram

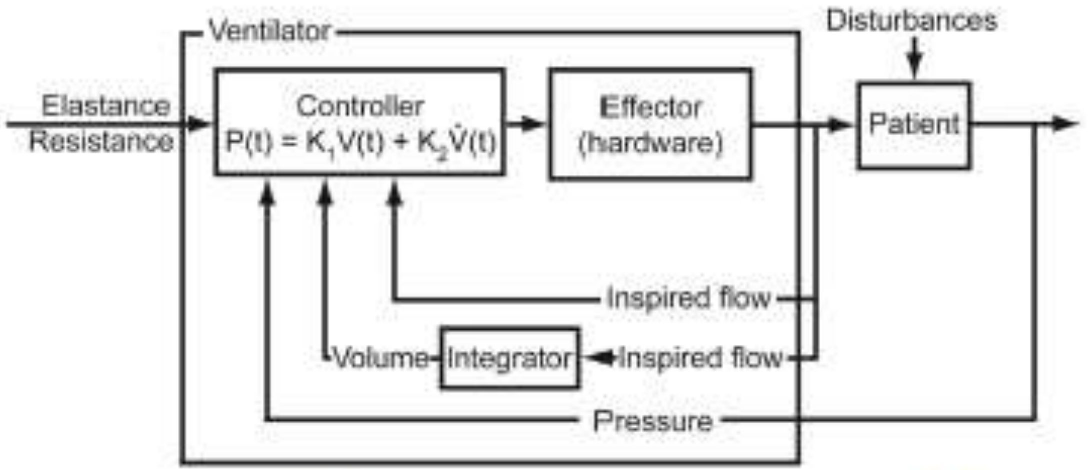
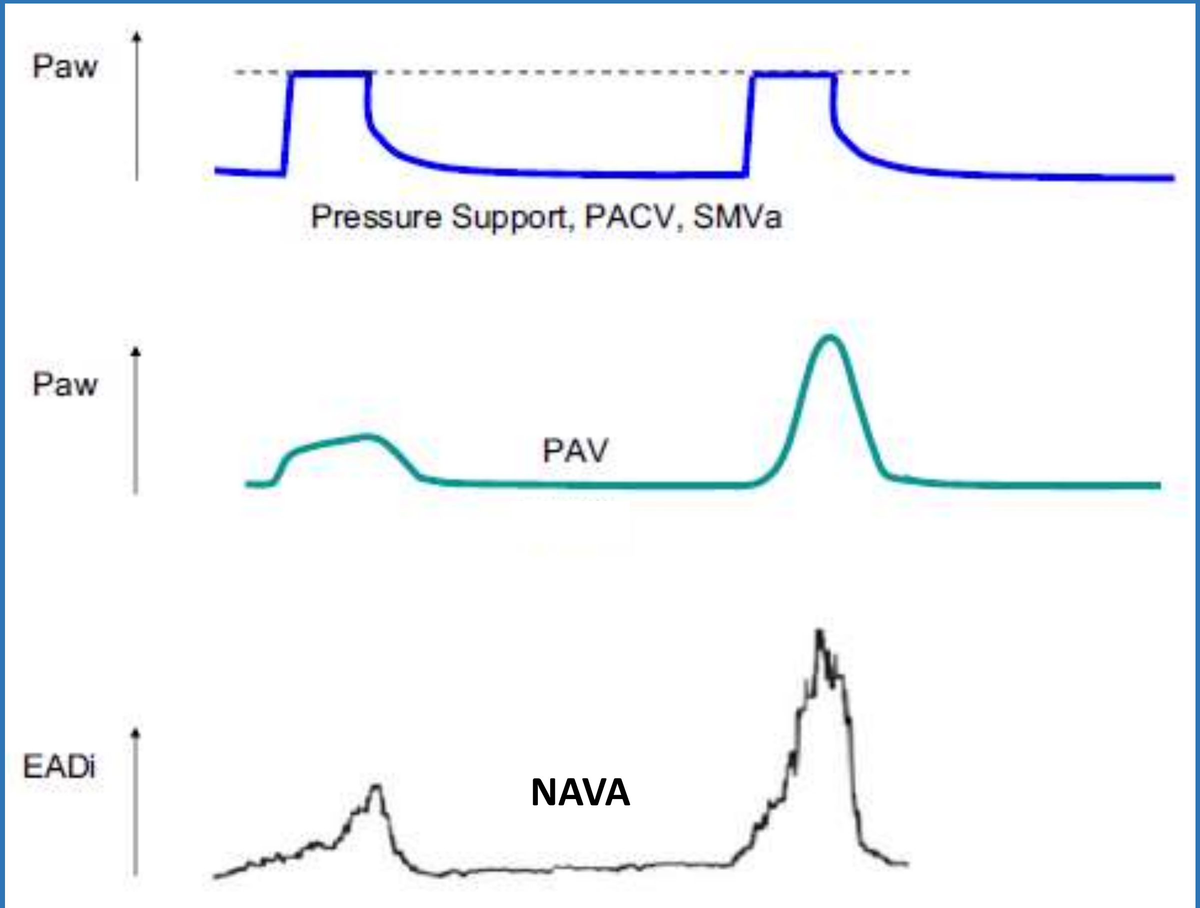
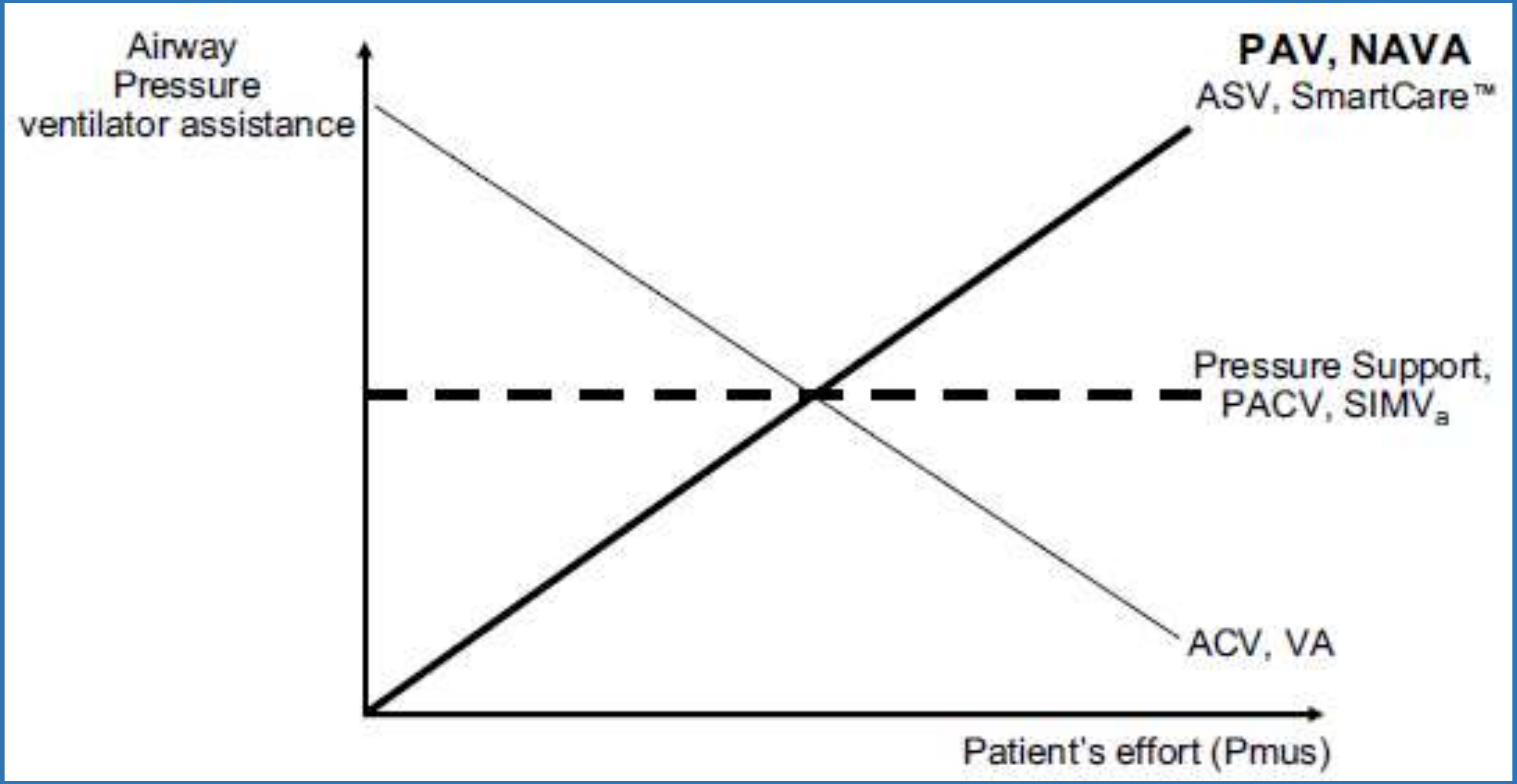


Fig. 5. Control circuit for a servo targeting scheme (eg, Proportional Assist Ventilation). The controller is designed so that inspiratory pressure as a function of time (P(t)) is proportional to both volume as a function of time (V(t)) and flow as a function of time ($\dot{V}$(t)). The constant of proportionality K_1 represents the amount of elastance to be supported. The constant of proportionality K_2 represents the amount of resistance to be supported.

Comparison of Flow-Time curves





Airway
Pressure
ventilator assistance
PAV, NAVA
ASV, SmartCare™
Pressure Support,
PACV, SIMV$_a$
ACV, VA
Patient's effort (Pmus)

Gain Setting

- The proportionality between flow and Paw,insp is determined by a “gain setting”, which is adjusted by clinician
- Gain based on the patient’s respiratory mechanics, resistance (Rrs) and compliance (Crs) of the respiratory system
- To use PAV correctly, Rrs and Crs should be evaluated continuously and the Gain adjusted accordingly
- This setting determines the proportion of the total work of breathing that will be done by the ventilator

ADVANTAGES

- Adapts to Ventilatory demand and load of patient
- Better patient synchrony and comfort
- Greater breath-to-breath variability allowing more physiological breathing
- Better Sleep and less awakenings

DISADVANTAGES

- Complexity
- Resistance, Compliance has to be estimated
- Lung mechanics may change over hours – Rrs and Crs have to be frequently monitored and entered
- If Gain setting not optimal → Instability
- There should be no leaks

Variations

A. Drager Evita XL – “Proportional Pressure Support”

Both elastance and resistance manually entered by clinician

ATC also available – but level of compensation set manually

B. Puritan Bennett 840 – “PAV +”

Ventilator itself calculates Elastance and Compliance continuously

ATC level too set automatically

Gain values better estimated – Less Instability

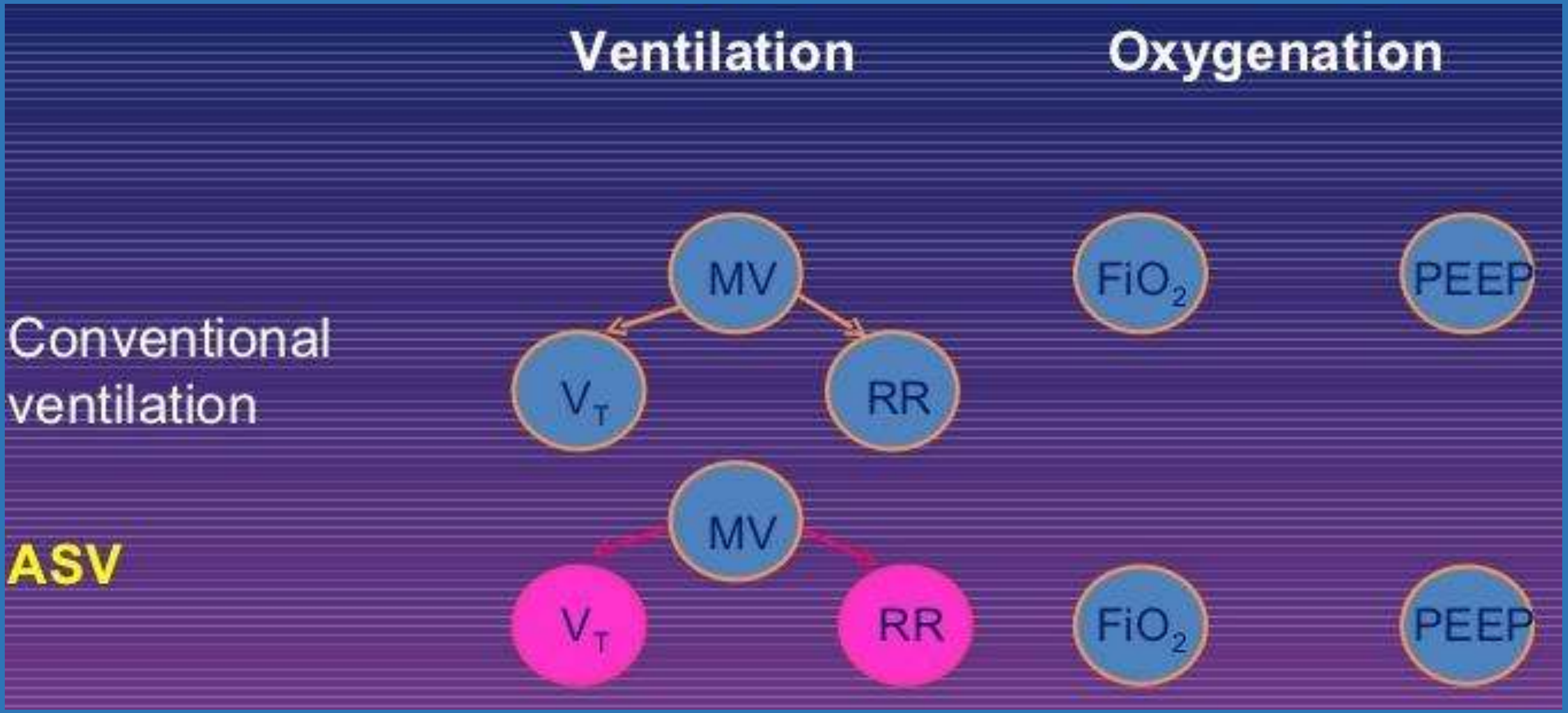
Decreases number of Manual adjustments

Adapts to changing lung mechanics

Automatic Modes

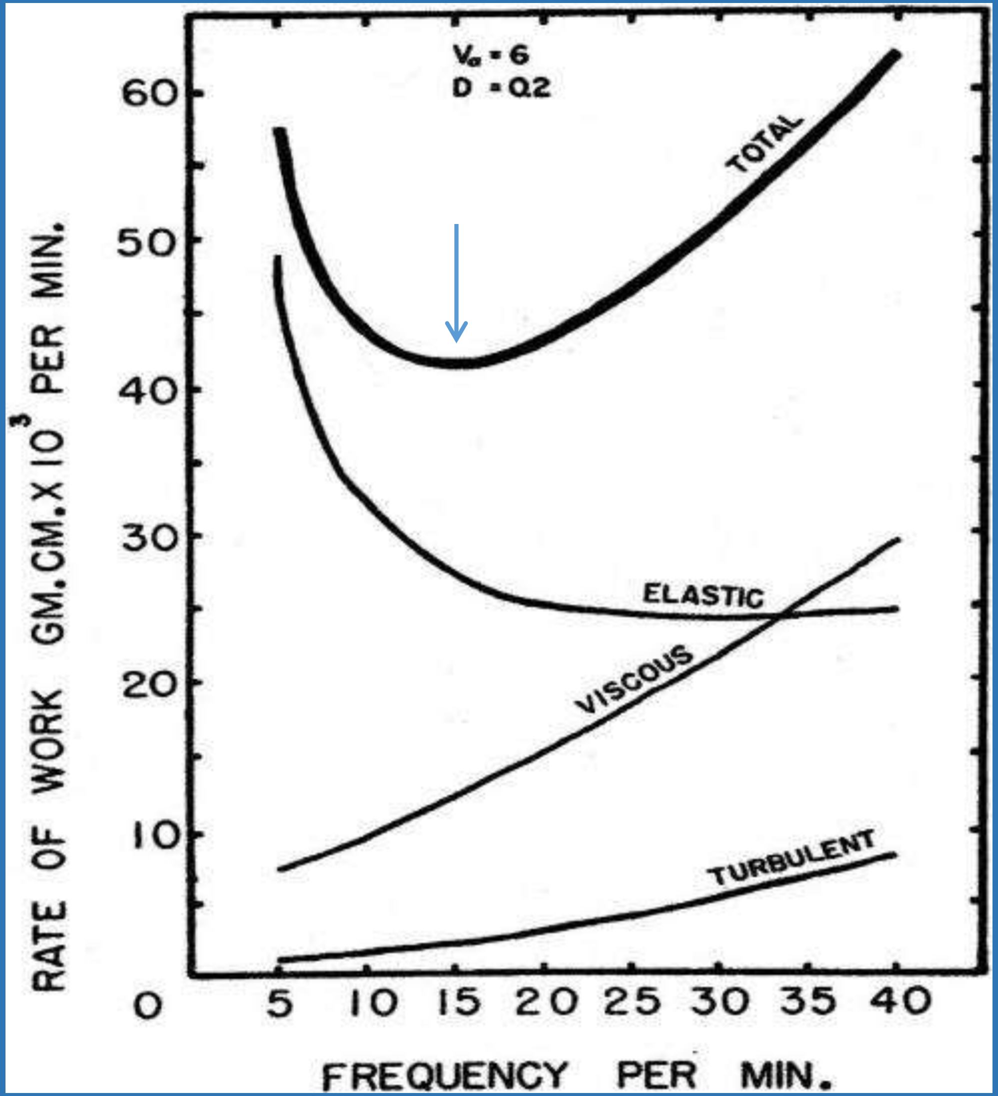
- ASV
- SmartCare
- IntelliVent

Adaptive Support Ventilation



MV = Minute Ventilation

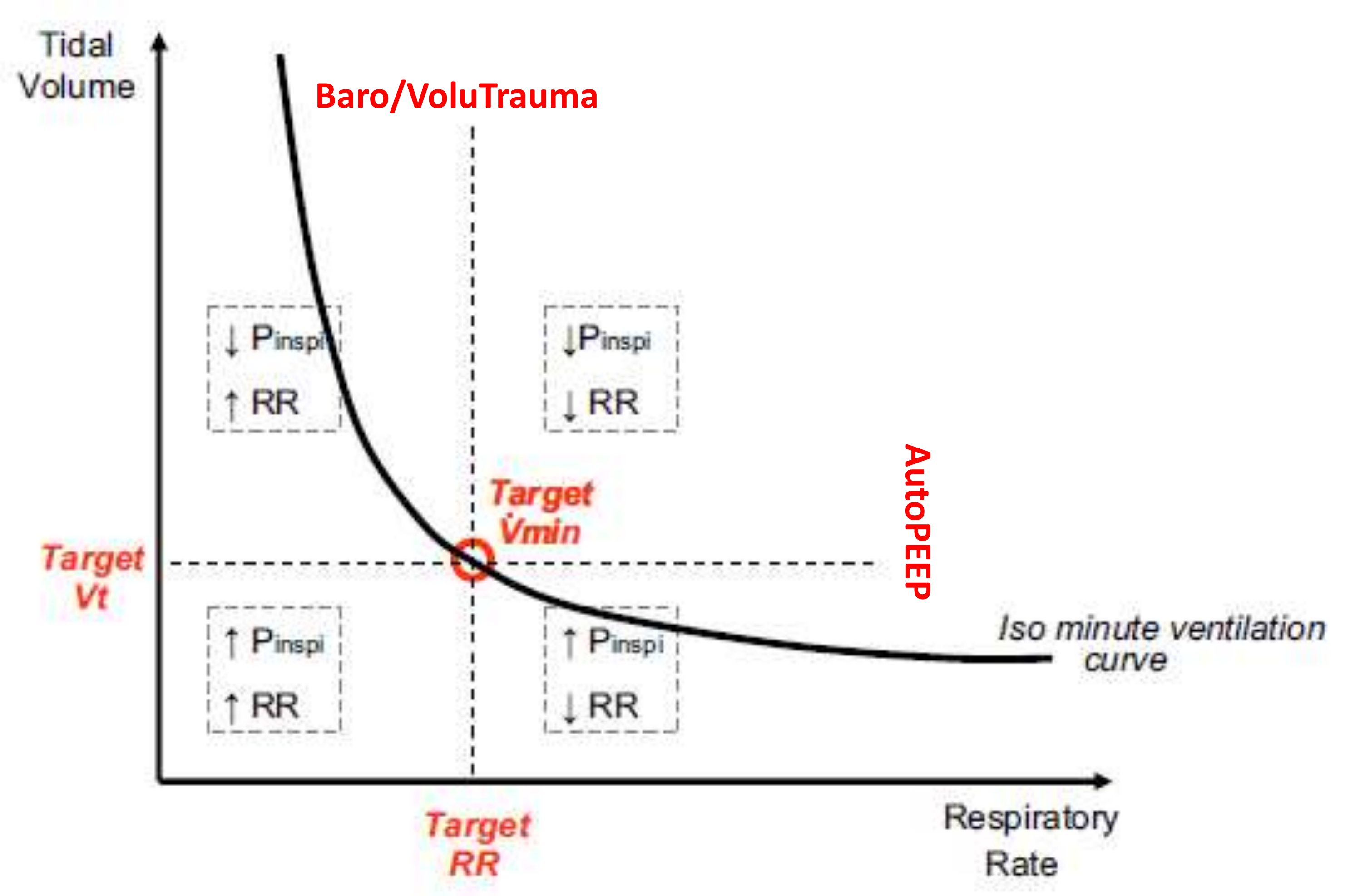
Principle



- Based on equation given by Otis in 1950
- For given MV, WoB optimum at a particular frequency
- In ASV MV target is set as % of ideal MV
- 100% MV taken as 0.1 l/kg IBW
- Ventilator itself delivers required Pressure to maintain the MV based on feedback from patient

$$f = \frac{\sqrt{1 + 2a \times \mathrm{RC} \times \dfrac{\text{Min Vol} - (f \times V_d)}{V_d}} - 1}{a \times \mathrm{RC}}$$

The ASV Target Curve



Settings

To be set Manually

1. IBW
2. %MV
3. fiO2
4. PEEP
5. Pressure limit
6. Rate limit
7. Slope of pressurisation (Pramp)
8. Flow Trigger (2-3l/m)
9. Expiratory Trigger Sensitivity (25%)

Continuously analysed by Ventilator

1. Ppeak
2. Vt
3. RR
4. RC exp
5. Compliance

Automatically adjusted by Ventilator

1. Pinsp
2. I:E
3. Flow rate
4. RR (inactive patient)

MV Settings

- Normal 100%
- Asthma 90%
- Acute respiratory distress syndrome (ARDS) 120%
- Others 110%
- Add 20% if T body >38.5°C (101.3°F)
- Add 5% for every 500 m (1640 feet) above sea level

Working

- ASV operates in a closed loop to move closer to the minute ventilation target
- Automatically adjust the inspiratory pressure, the I/E ratio, and the respiratory rate (in the absence of cycles triggered by the patient) to achieve this objective
- Can theoretically be used from the initiation of mechanical ventilation in patients who make no respiratory effort to weaning phase when patient triggers all cycles, since this mode can deliver all cycles - controlled/assisted/spontaneous

Follow-up

	Adjustments % Min Vol	Comments
ABG Normal	None	
High PaC02	Increase % Min Vol	Check respiratory pressures
Low PaC02	Lower % Min Vol	Chech mean Pressure and oxygentacion
High respiratory drive	Consider increase % Min Vol	Consider sedation
Low 02 saturation	None	Consider increase PEEP or Fi02

Advantages and Disadvantages

Advantages	Disadvantages
Versatile and extremely safe to use	Does not allow direct programming of VT, RR and I:E ratio
Ventilate virtually all intubated patients actively or passively	Limited experience in pediatric patients
Prevents tachypnea, auto-PEEP and dead space	Operation algorithm tends to ventilate with low VT and high RR
Less need of human manipulation of the machine	Only available in Hamilton ventilators
Decreased time on the mechanical ventilation	
Adjusts to patient respiratory effort	

VT: Tidal volume; RR: Respiratory rate; auto-PEEP: Auto-positive end-expiratory pressure; I:E: Inspiratory:Expiratory

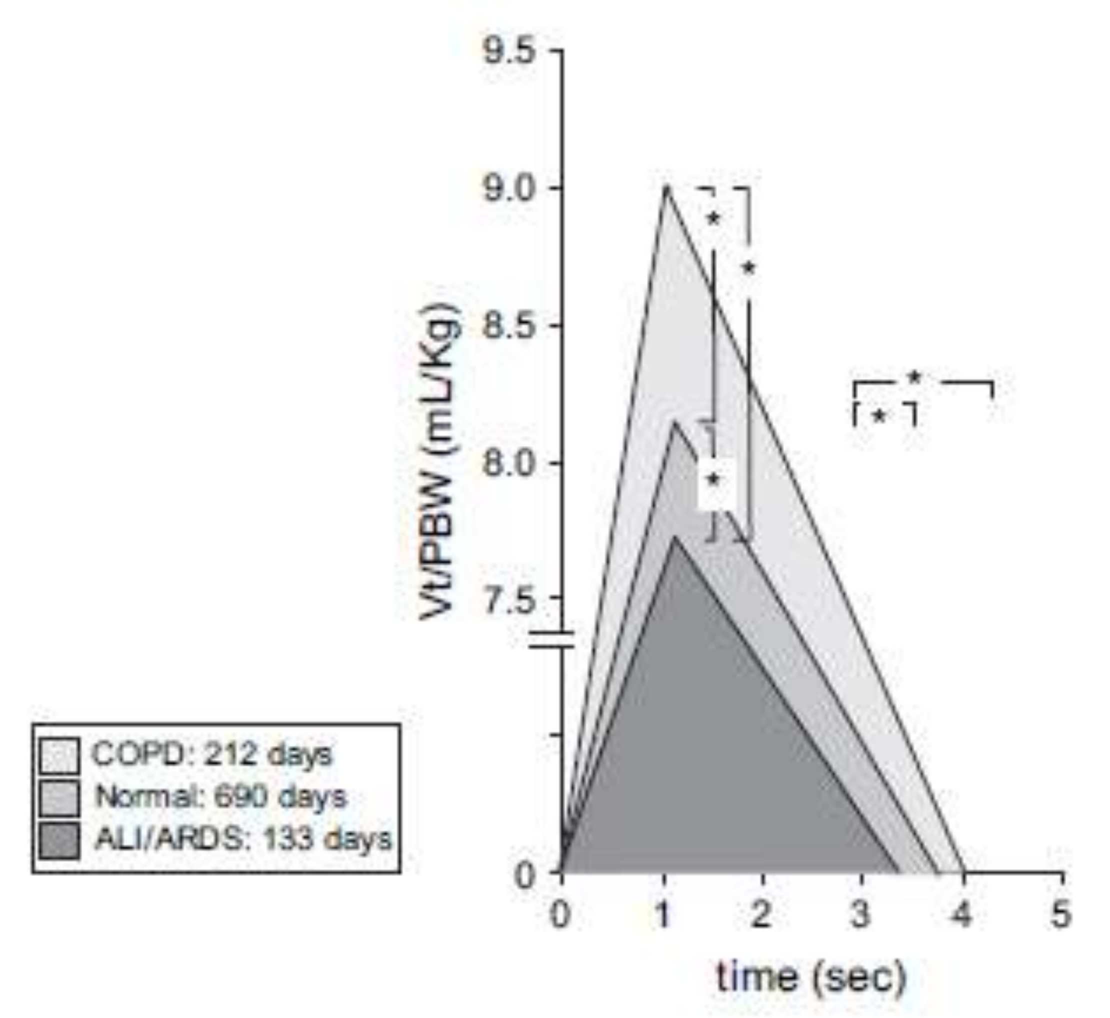
Ventilation delivered in various settings

	Normal	COPD	Chest wall restriction	ARDS
Days/patients	706/140	217/40	54/13	136/36
RC exp (sec)	0.78	1.13*	0.41*	0.55*
Vt/PBW (ml/kg)	8.3	9.4*	7.1*	7.6*
RR	17	16	23*	20*
I:E	0.5	0.4*	0.5	0.63*

*P-value <0.05

Arnal et al Intensive Care Medicine 2008

Ventilation delivered in various settings



*P-value <0.05

Arnal et al Intensive Care Medicine 2008

ASV in ARDS

- Study of 108 patients*
  - Delivered Vt ~ 6 ml/kg IBW
  - Achieves Same Pplat (<30) as that in ARDS-Net Protocol
  - Delivers Lower Vt and Pplat depending on the case severity

*Sulemanji et al, Anesthesiology, 2009

- Study of 51 patients*
  - Vt ~ 6 ml/kg
  - Pplat < 28

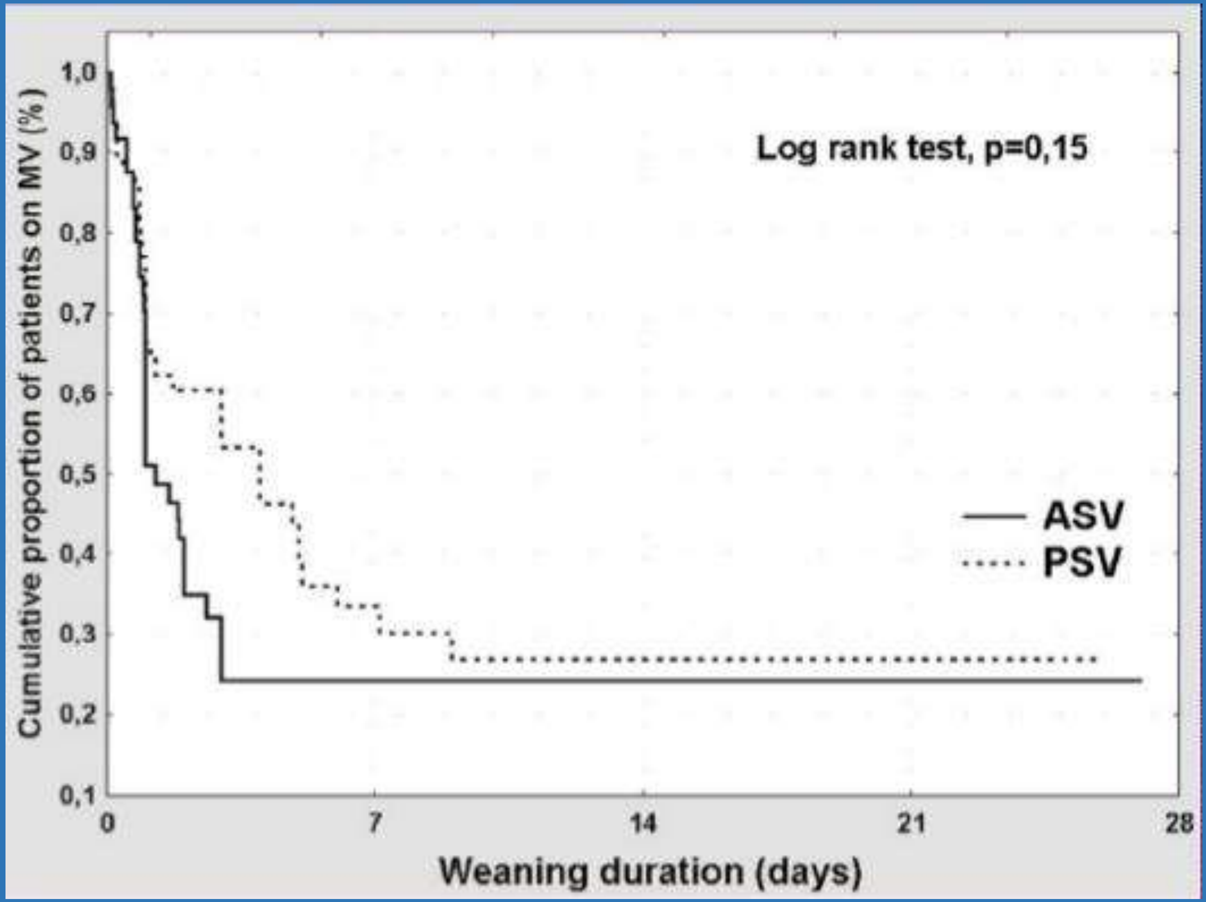
*Arnal et al, AJRCCM, 2007

ASV in Weaning

	Number of patients	Hours of MV Control (PSV)	Hours of MV (ASV)	P-Value
Sultzer et al, 2001	36	4	3.2	<0.02
Petter et al, 2003	34	3.2	2.7	NS
Gruber et al, 2008	48	8	2.7	<0.05
Dongelmans et al, 2009	121	16.3	16.2	NS

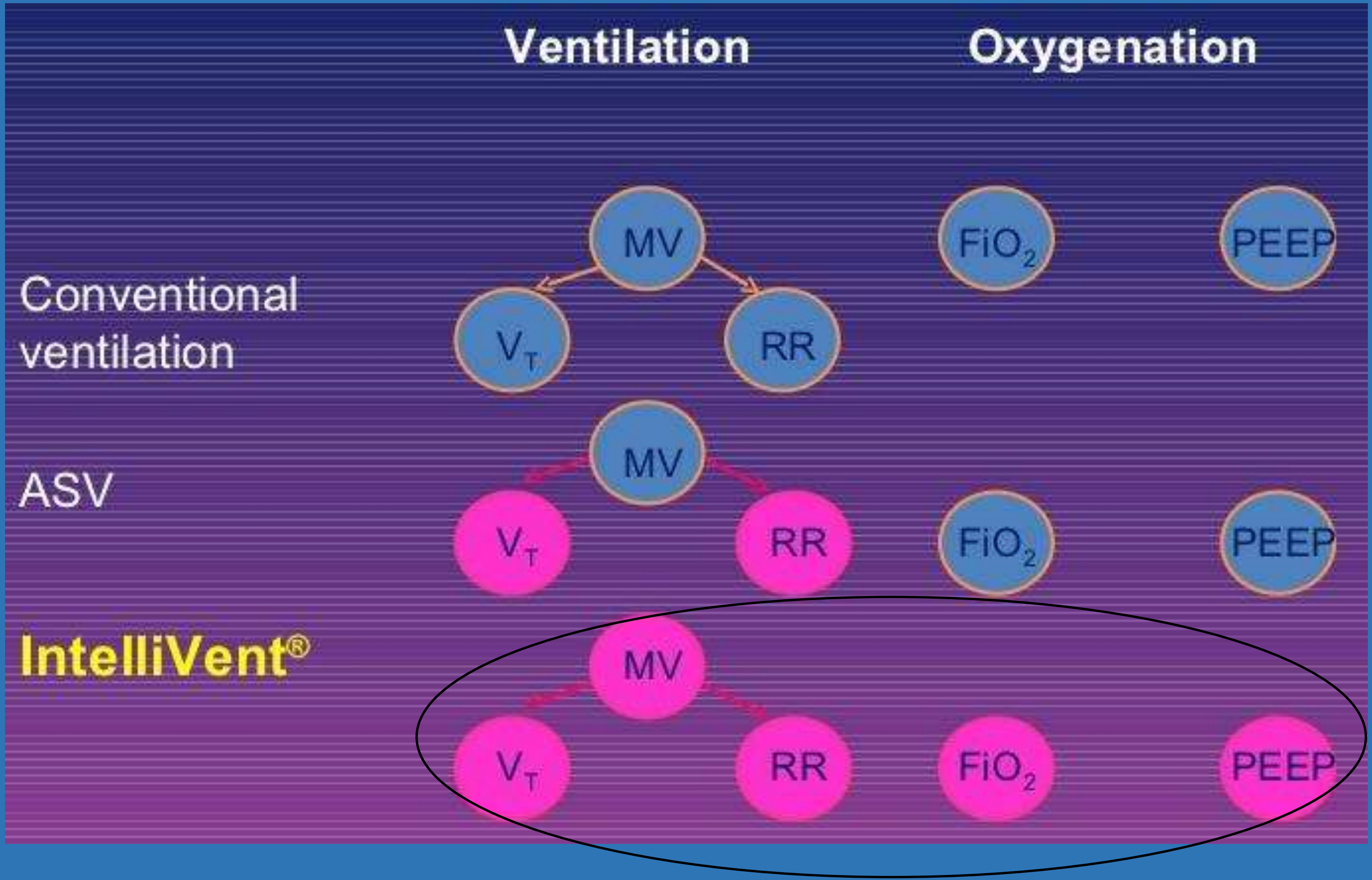
ASV in COPD

N=97



Kirakli et al, Eur Resp J, 2003

Intellivent



Intellivent

- Claimed to be First complete Closed Loop system
- Only 3 parameters need to be entered
  - PEEP
  - fiO2
  - %MV
- Based on EtCO2 and SpO2 – Even theses parameters maybe automatically controlled!

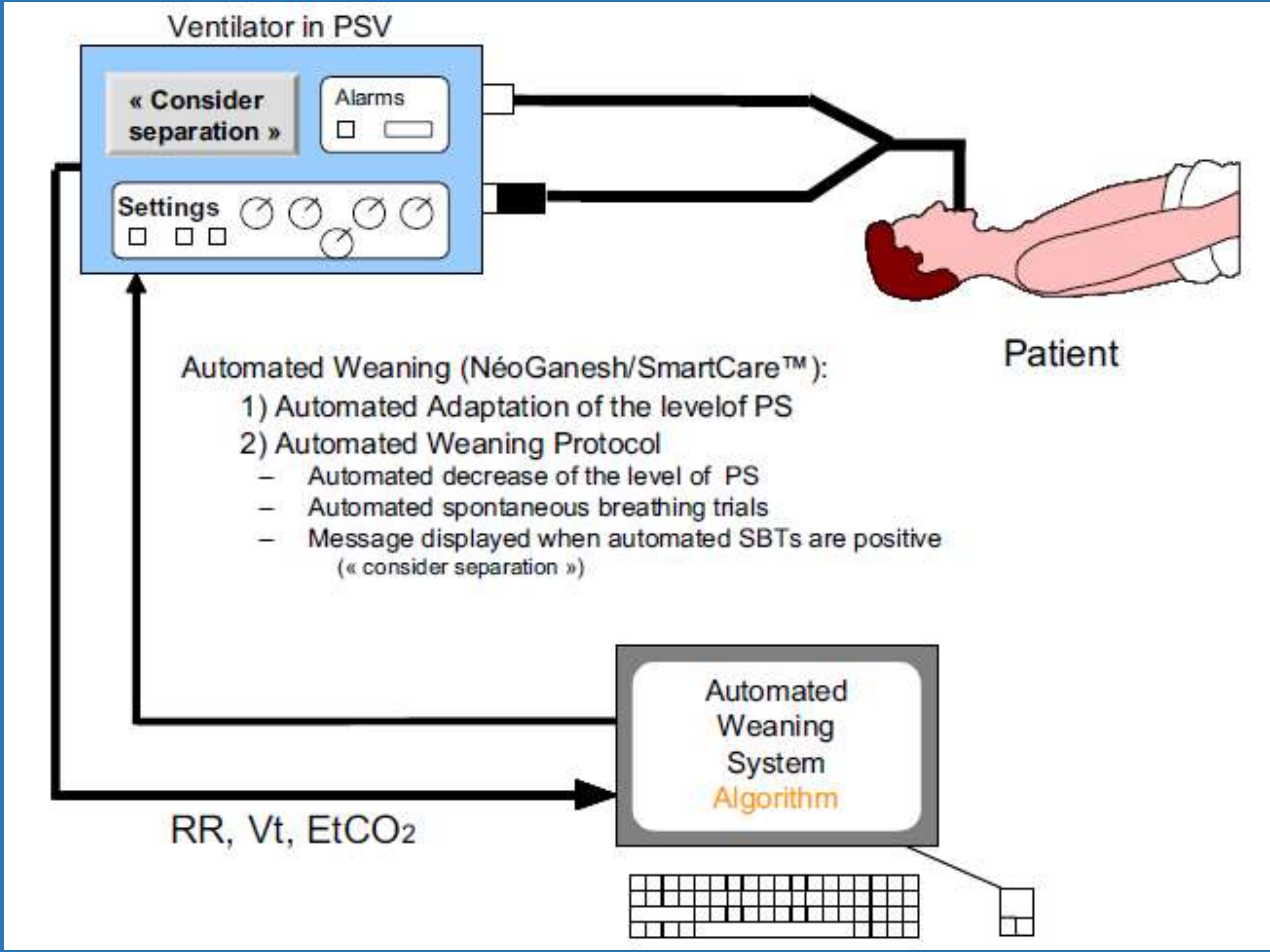
NeoGanesh (SmartCare)

- Knowledge based Weaning System
- Basically an “Intelligent” form of PSV
- Principles:

(1) to maintain the patient in a respiratory ‘comfort zone’ by adapting the level of pressure support

(2) to gradually decrease the level of the pressure support in case of stability

(3) to implement automated spontaneous breathing trials (i.e. weaning tests) performed with minimal levels of pressure support, this last phase being followed by a message on the screen if those tests are positive.


Ventilator in PSV
« Consider separation »
Alarms
Settings
Patient
Automated Weaning (NéoGanesh/SmartCare™):
1) Automated Adaptation of the levelof PS
2) Automated Weaning Protocol
– Automated decrease of the level of PS
– Automated spontaneous breathing trials
– Message displayed when automated SBTs are positive
(« consider separation »)
Automated Weaning System
Algorithm
RR, Vt, EtCO2

Multicentre study of SmartCare

- Five academic centres recruited 144 patients in 1 year
- Patients included as soon as they could tolerate PSV and met criteria for early weaning
- 74 patients ventilated with SmartCare system, and 70 were weaned through usual care
- With the automated weaning system the weaning duration was reduced from a median of 4 days to 2 days (P 0.02)
- Total duration of mechanical ventilation was reduced from 12 to 7.5 days

  (P 0.003).
- Median duration of ICU stay was reduced from 15.5 to 12 days (P 0.02)
- Proportion of patients requiring non-invasive ventilation after extubation was reduced from 37% to 19% (P 0.02)
- The proportion of patients requiring mechanical ventilation for more than 21 days was 7% with the automated system weaning versus 16% (p 0.11)

Lellouche et al, AJRCCM 2006

Conclusion

- In future → Ventilators will adapt themselves to the patient and not the other way round
- Can significantly help in decision making and reducing work burden on ICU staff
- Patient comfort, weaning time, intubation time all may be decreased
- However the newer modes have to give solid proofs of their usefulness
- Clinicians have to use critical thinking on their part to separate the real innovations from “gimmicks” and evaluate their usefulness…