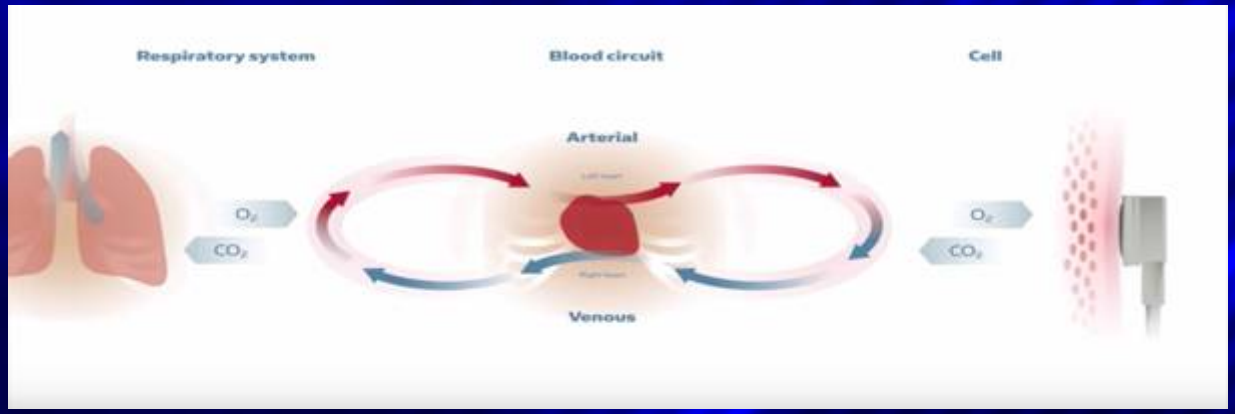
Transcutaneous Monitoring: *Beyond Neonatal Applications*

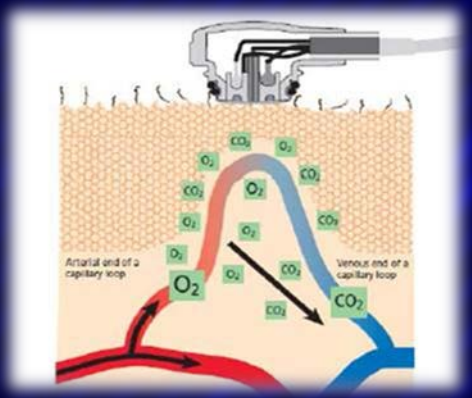


UT Health San Antonio
uthscsa.edu

Ruben D. Restrepo, MD, RRT, FAARC
Professor
Department of Health Sciences
Division of Respiratory Care

Objectives

- Describe the need for continuous CO_2 monitoring
- Review general concepts and principles of operation of TCM
- Compare and contrast different methods used for continuous non-invasive monitoring of CO_2
- Review the role of digital TCM in some relevant clinical settings
  - OIRD
  - Sleep diagnostics
  - NIV titration



Introduction

- Respiratory system consists of two parts
  - Lungs = facilitate gas exchange
  - Respiratory pump = drives ventilation
- Type I respiratory failure = hypoxemic
- Type II respiratory failure = hypercapnic
- Historically, physicians were only able to examine the respiratory pump by physical examination
- Today, PCO_2 measurement is integral aspect of the Dx and Tx of patients with respiratory failure

Severinghaus JW, Astrup P, Murray JF. *Am J Respir Crit Care Med* 1998;157:114-122.

Blood Gas Measurement

- Relationship between an elevated PCO_2 and reduced alveolar ventilation discovered in 1952 (polio epidemic in Copenhagen)
- Since then = several methods for PCO_2 assessment

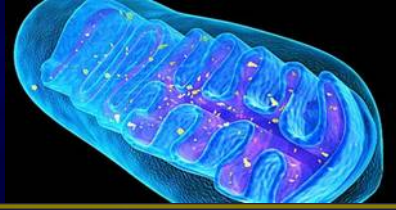
arterial	**venous**	**capillary**
end tidal	**transcutaneous**	

- Acute and chronic respiratory failure
- Medical procedures (endoscopy)
- Differ considerably

indications	**accuracy**
side effects	**availability**
contraindications	
capacity to facilitate continuous assessment	
ability to assess additional information	

- Different techniques are not competitive, but rather complementary
- Reasonable to combine techniques depending on specific clinical scenarios

Physiology of CO_2



- CO_2 = product of cellular metabolism (Kreb's cycle) – mitochondria
- CO_2 enters the bloodstream (diffusion) and reaches the pulmonary capillaries (convection)
- Diffuses through the alveolar membrane into the alveoli = eliminated via the airways
- Alveolar (~ 40 mmHg) - capillary (~ 46 mmHg) difference (P_{A-a} CO_2) is rather small = **CO_2 has excellent solubility**
- CO_2 mainly dissolves in water to produce H_2CO^3, which, in turn, converts into $HCO3^-$ and protons (H^+).
- Only a small amount of CO_2 remains physically dissolved
  - can be detected by PCO_2 monitoring

Milestones in pCO_2 Monitoring Techniques

1754
Joseph Black
discovers „fixed air“
in exhaled air

1777
Antoine Lavoisier „fixed air“ = compound of coal and product of respiration

1797
Sir Humphry Davy
existence of CO_2 in blood

1845
Heinrich G. Magnus arterio-venous difference of CO_2

1877
Friedrich Walter
CO_2 ~ blood alkalinity

1905
Max Cremer
potential difference between different acidities

1907 Henderson equation

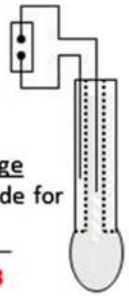
*

$$[H^+] \times [HCO_3^-] = K \times [CO_2] \times [H_2O]$$

1917
$$pH = pK + \log([HCO_3^-] / [CO_2])$$
Henderson-Hasselbalch equation

1924
Donald D. Van Slyke
determination of CO_2 by vacuum extraction

1925
Phyllis T. Kerridge
first pH-electrode for blood



1943
Karl Luft
modern capnograph using infra-red

1952
Polio epidemic in Copenhagen

Poul Astrup
PCO_2 by interpolation

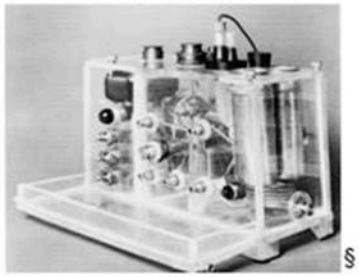
Bjørn Ibsen
respiratory failure → high CO_2 levels

†

1957
Richard W. Stow
first PCO_2-electrode

1958
John W. Severinghaus
improves stability and sensitivity by adding $NaHCO_3$

1959
Severinghaus and Bradley
first three-function blood gas apparatus



§

1960
John W. Severinghaus
measurement of PCO_2 on human skin

Severinghaus Electrode

- Richard W. Stow created the first electrode for measuring PCO_2 in 1957.
- He constructed a glass pH electrode wrapped in a thin, CO_2-permeable rubber membrane.
- John W. Severinghaus showed in 1958 that the stability and sensitivity of the electrode could actually be enhanced by adding $NaHCO_3$.
- This PCO_2-electrode remains to this day the basic technique for PCO_2- measurements.

Stow RW, Baer RF, Randall BF. *Arch Phys Med Rehabil* 1957;38:646-650.
Severinghaus JW, Bradley AF. *J Appl Physiol* 1958;13:515-520.
Hahn CE. *J Phys E* 1980;13:470-482

Transcutaneous PCO_2-Sensor

- In 1960 Severinghaus described the measurement of PCO_2 via human skin, using a specially designed, temperature-stabilized tissue PCO_2 electrode.
  - Technique further developed by local heating = continuous measurement of blood gases by arterialization of cutaneous tissue

Severinghaus JW. *Anesthesiology* 1960;21717-26.
Binder N, et al. *Am J Perinatol* 1994;11:237-24.
Dullenkopf A, et al. *Paediatr Anaesth* 2003;13:777-784.
Mindt W, et al. *Biotelem Patient Monit* 1982;9:28-35.
Eberhard P, et al. *Anesth Analg* 2002;94Suppl:S76-80.
Kocher S, et al. *J Clin Monit Comput* 2004;18:75-79.

Transcutaneous PCO_2-Sensor

- In 1970s, $PtcCO_2$ and $PtcO_2$ were first established in neonates and infants.
- New generation $PtcCO_2$-monitors comprised a combined $PtcCO_2$-SpO_2-sensor
- Recent developments in signal digitalization have led to the shortening of reaction times and more robust signals.

Severinghaus JW. *Anesthesiology* 1960;21717-26.
Binder N, et al. *Am J Perinatol* 1994;11:237-24.
Dullenkopf A, et al. *Paediatr Anaesth* 2003;13:777-784.
Mindt W, et al. *Biotelem Patient Monit* 1982;9:28-35.
Eberhard P, et al. *Anesth Analg* 2002;94Suppl:S76-80.
Kocher S, et al. *J Clin Monit Comput* 2004;18:75-79.

Transcutaneous Monitoring

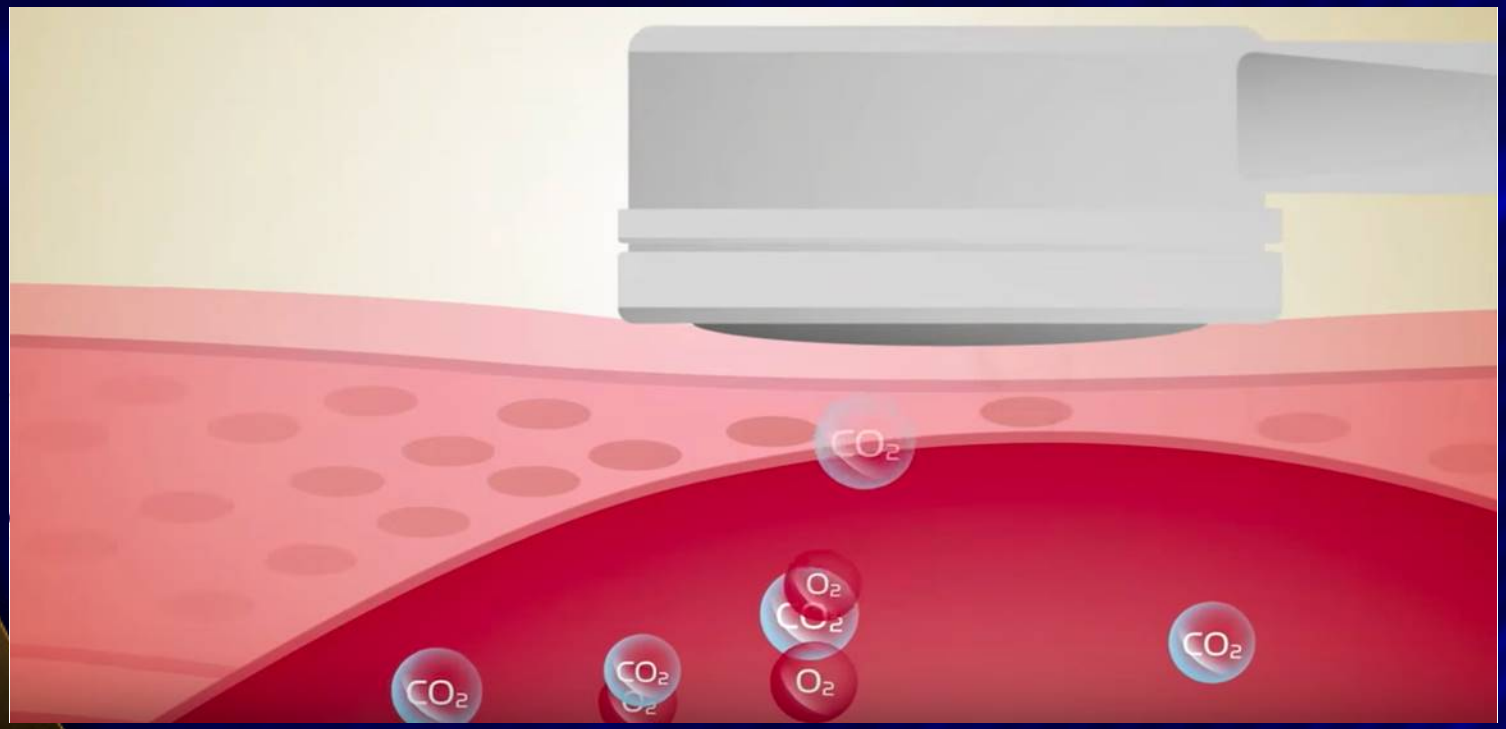
- SpO_2 has been considered standard of care for noninvasive monitoring of oxygen levels
  - Routine $PtcO_2$ has fallen out of favor
- Most studies are focused on $PtcCO_2$
- Considered an accurate and clinically acceptable estimate of the $PaCO_2$

Transcutaneous Monitoring

- **Principles of operation**
  - Heating element to improve gas diffusion
  - P_CO_2 slightly lower than arterial
  - **P_CCO_2 slightly higher than arterial**
    - **TCM = metabolic correction**
- **Application**
  - Most critical aspect is **site selection and application**
  - Temperature range 41C° to 44 C°
  - Change site every 4 to 12 hours

Principles of Operation

- The TCM heating element induces hyperperfusion of underlying capillaries.
  - Typical arterialization time: 3-10 minutes



Principles of Operation

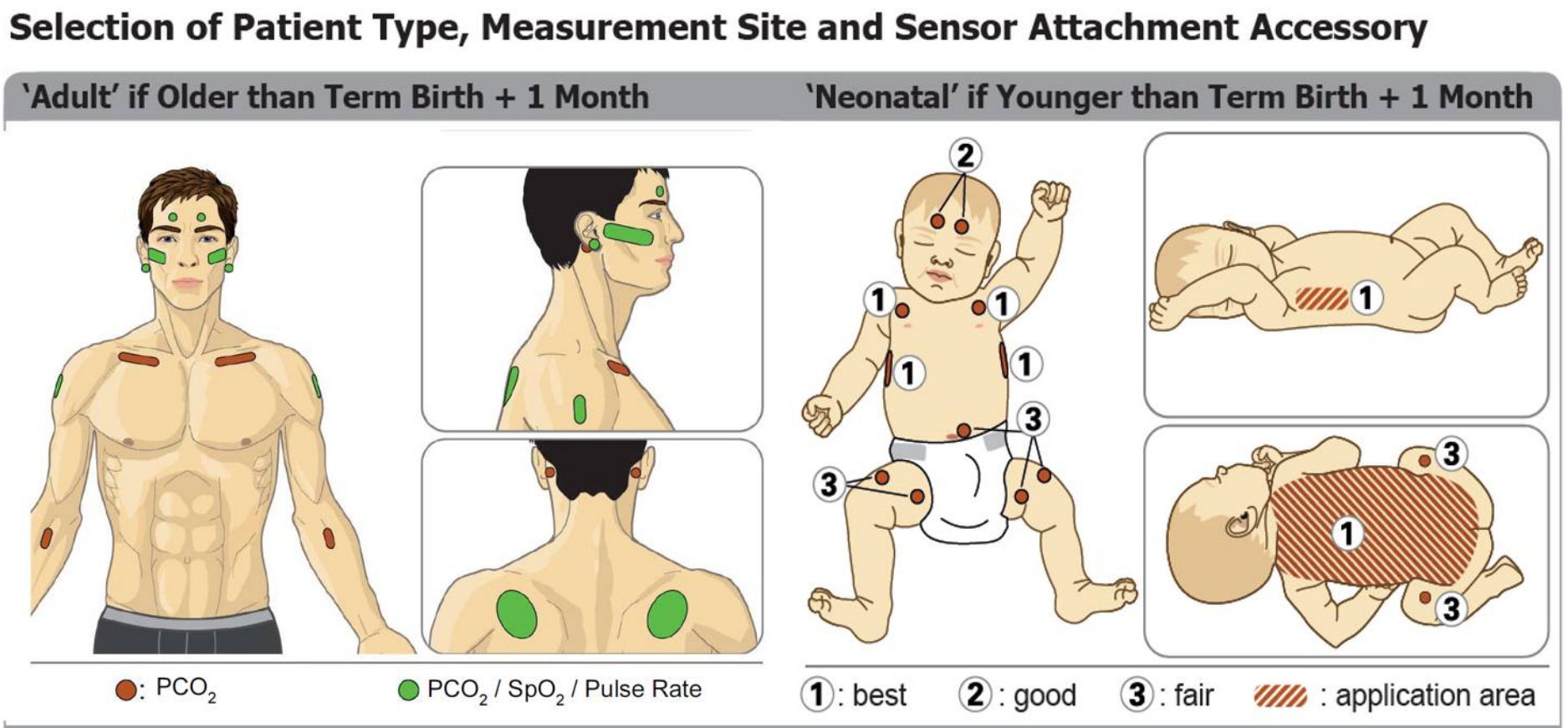
- The TCM heating element induces hyperperfusion of underlying capillaries.
- Externally applied heat
  - alters the solubility of CO_2 in the blood
  - ↑ metabolic rate of the skin by approximately 4–5%/1C° = local production of CO_2.
- A thin electrolyte layer is confined to the sensor surface with a CO_2 permeable membrane contacting the patient's skin during monitoring.
- Sensor measures CO_2 by a change in pH of the electrolyte solution
  - and calculates $PaCO_2$ estimates by correcting temperature to 37°C and subtracting an estimate of the subtracts an estimate of the local 'Metabolic Offset'

Principles of Application

1. Sensor calibration
2. Fixation device is in place
3. Addition of 1–2 drops of contact gel or NS inside the ring
   - improves the accuracy of the sensor and makes the diffusion of gases more efficient.
4. Placement of sensor into the ring - snaps into place.
   - The ring must create enough of a seal to prevent leaks or formation of air bubbles, as ambient air reaching the sensor affects measured values.

Principles of Application

- Skin must be cleaned of all oils, soaps, and dead skin.
- Sensor fixation ring in highly vascularized area
- Preferred location in neonates and small patients is the upper chest.



Principles of Application

- In order to achieve accurate $PtcO_2$ the skin probe temperature must be 43-44°C
  - bears risk of erythema or burning of the skin
  - risk gradually increases with increasing exposure time
  - particularly in patients with thin or damaged skin.
- By contrast, monitoring of the $PtcCO_2$ is reliable with skin probe temperature even as low as 37°C.
  - Most TC monitors allow the reduction of the probe temperature to minimize the risk of thermal injury to 40°C.

Device Limitations

TECHNICAL

- Labor intensive
- Prolonged stabilization time

CLINICAL

- Presence of shock or acidosis
- Improper electrode placement
- Use of vasoactive drugs
- Nature of patient's skin
  - Skinfold, thickness, edema
- Room/skin temperature too low
  - Decrease blood flow to epidermis

Complications

- Thermal injury at measuring site
  - Erythema
  - Blistering
  - Burns
  - Epidermal stripping

SITE PROTECTION

Site Timer

Low priority alarm

Reduces sensor temperature

Minimizing Discrepancy

- Obtain ABG to validate TCM values
  - Initially and periodically
- Practitioner should routinely verify
  - High and low limit alarms
  - Proper electrode placement
  - Electrode site changes

TCM DOES NOT REPLACE ABGs

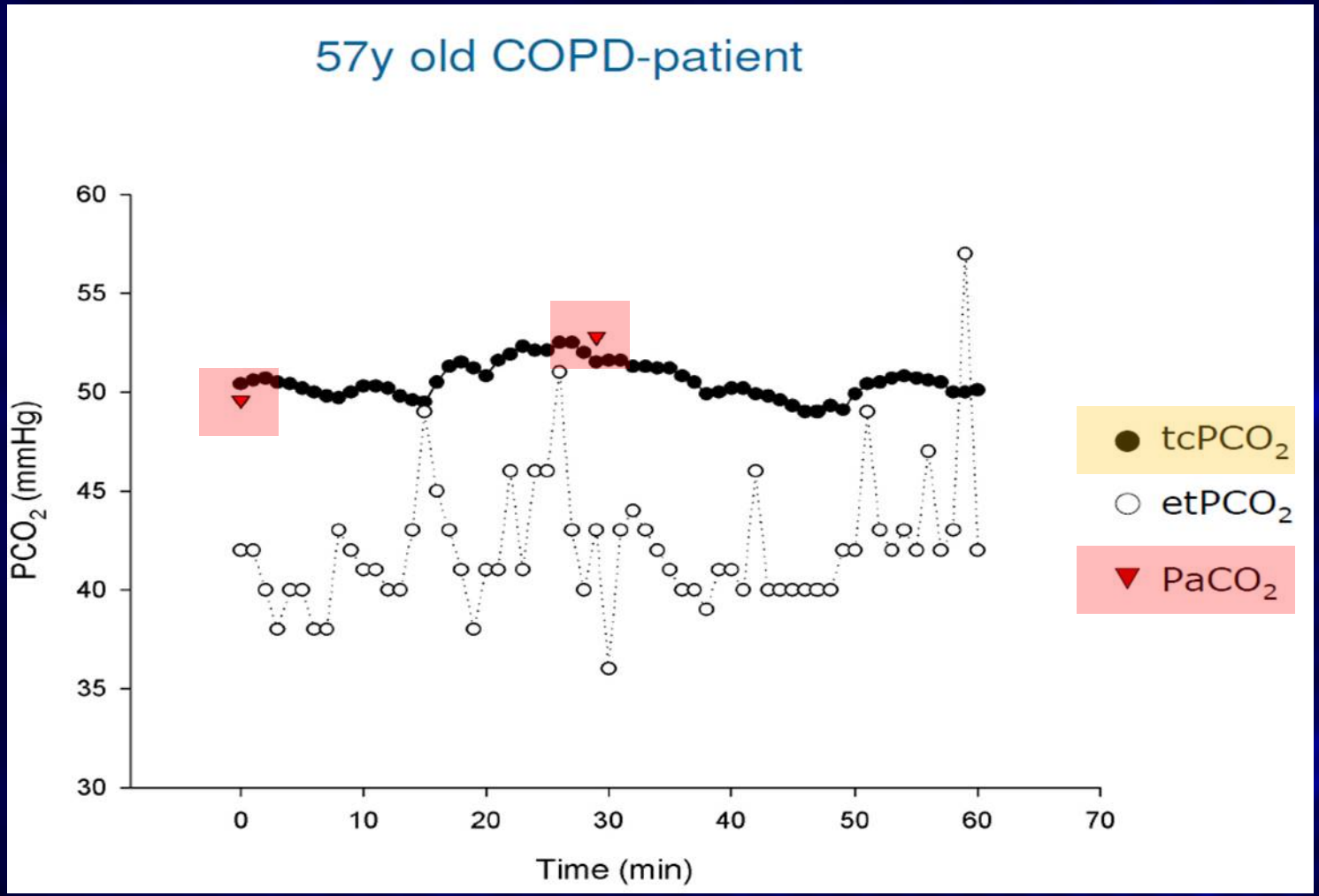
It minimizes blood drawings

Good indicator when they need to be obtained

Progress Made on TCM

- Combination with SpO_2
- Use of lower sensor temperature
- Decrease size of the sensor
- Digitalization of the signal of the sensor
- Calibration intervals up to 12 hours
- Site protection
- Sophisticated artifact detection
- Semi-automated membrane changer
- Direct interface to major patient monitoring systems

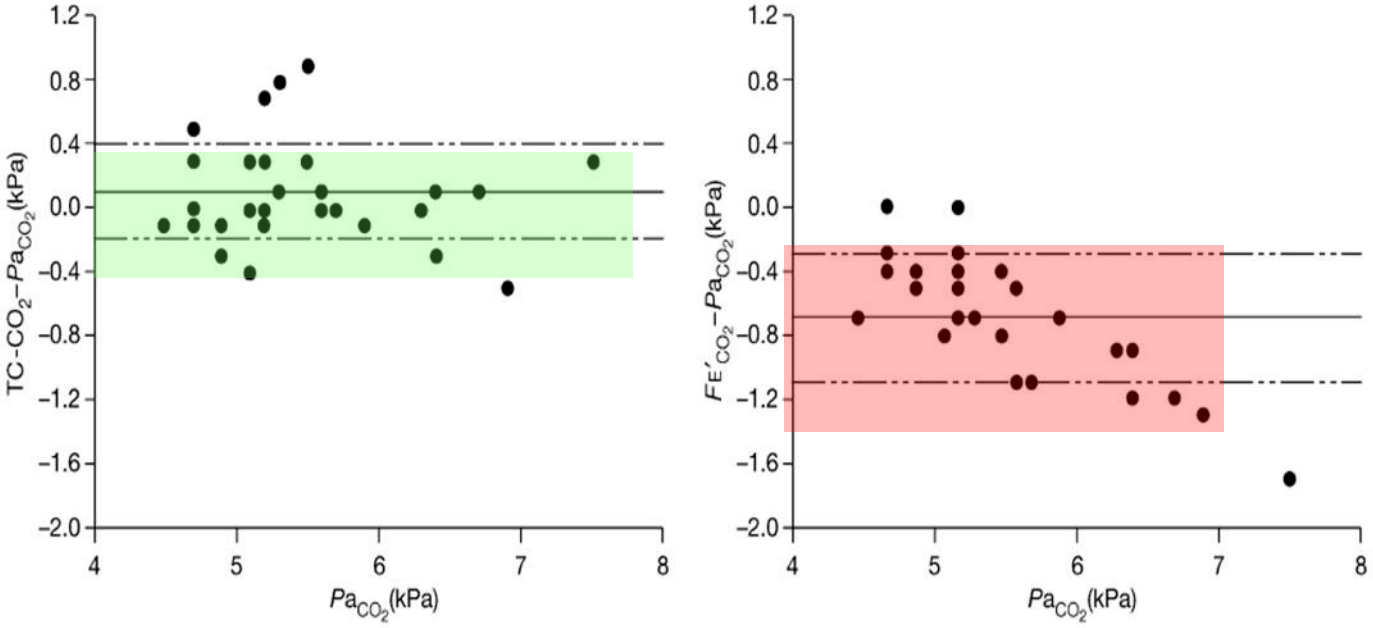
tcpCO2 vs. etCO2



Storre J, Dellweg D, Pneumologie 2014, s-0034-1365742

Comparison of end-tidal and transcutaneous measures of carbon dioxide during general anaesthesia in severely obese adults

J. Griffin[1], B. E. Terry[2], R. K. Burton[1], T. L. Ray[1], B. P. Keller[1], A. L. Landrum[1], J. O. Johnson[1] and J. D. Tobias[1]*



Conclusions. Transcutaneous carbon dioxide monitoring provides a better estimate of Pa_{CO_2} than FE'_{CO_2} in patients with severe obesity.

British Journal of Anaesthesia **91** (4): 498–501 (2003)

AARC Clinical Practice Guideline: Transcutaneous Monitoring of Carbon Dioxide and Oxygen: 2012

Ruben D Restrepo MD RRT FAARC, Keith R Hirst MSc RRT-NPS, Leonard Wittnebel MSIS RRT, and Richard Wettstein MMEd RRT

Development, and Evaluation (GRADE) criteria: (1) Although P_{tcCO_2} has a good correlation with P_{aCO_2} and is a reliable method to evaluate plasma CO_2 levels, it is recommended that arterial blood gas values be compared to transcutaneous readings taken at the time of arterial sampling, in order to verify the transcutaneous values, and periodically as dictated by the patient's clinical condition. (2) It is suggested that P_{tcCO_2} may be used in clinical settings where monitoring the adequacy of ventilation is indicated. (3) It is suggested that P_{tcO_2} and P_{tcCO_2} may be used in determining the adequacy of tissue perfusion and monitoring of reperfusion. (4) It is suggested that TCM should be avoided in the presence of increased thickness or edema of the skin and/or subcutaneous tissue where the sensor is applied. (5) It is recommended that sites used for a TCM be changed as often as necessary and that they be alternated and observed to avoid thermal injury. Manufacturer recommendations should be followed. *Key words: clinical practice guidelines; hyperbaric oxygen*

has fallen out of favor. While some studies in infants[1-3] have shown that TCM of P_{O_2} may be more reliable than

TCM 2.0 DESCRIPTION/DEFINITION

A transcutaneous (TC) monitor measures the skin-surface P_{O_2} and P_{CO_2} to provide an estimate of the P_{aO_2} and

Dr Restrepo, Mr Wittnebel, and Mr Wettstein are affiliated with the Department of Respiratory Care, The University of Texas Health Sciences Center at San Antonio, San Antonio, Texas. Mr Hirst is affiliated with the Department of Respiratory Care, Rush University, Chicago, Illinois.

Dr Restrepo has disclosed relationships with Oridion and Teleflex. The other authors have disclosed no conflicts of interest.

Correspondence: Ruben D Restrepo MD RRT FAARC, Department of Respiratory Care, The University of Texas Health Science Center at San Antonio, MSC 6248, San Antonio TX 78229. E-mail: restrepor@uthscsa.edu.

DOI: 10.4187/respcare.02011

tcpCO2 vs. etCO2

- $tcpCO_2$ DOES NOT depend on “healthy lungs” or good lung perfusion/ventilation.
- $tcpCO_2$ therefore is preferred in patients with V/Q mismatch
  - One-lung ventilation
  - COPD
  - ARDS

Clinical Applications

- Different techniques of PCO_2 monitoring are used
- PCO_2 monitoring is used in patients with
  - acute and chronic respiratory failure
  - undergoing endoscopic procedures
  - general anesthesia

Primary Clinical Applications of Different PCO_2 Monitoring Techniques

Clinical Applications	ABG	CBG	VBG	PetCO2	PtcCO2
ICU	+	-	-	+	+
ER	+	-	+	-	-
Acute respiratory failure	+	-	-	-	-
Chronic respiratory failure	+	+	-	-	+
Invasive mechanical ventilation	+	+	-	-	-
Noninvasive mechanical ventilation	+	+	-	-	+
Screening for nocturnal alveolar hypoventilation	-	+	-	-	+
General anesthesia	+	-	-	+	+
Sedation in patients at risk for hypoventilation	+	-	-	+	+
Resuscitation	+	-	-	+	-
Screening for hypercapnia	+	+	+	+	+
Confirm and monitor tube placement	-	-	-	+	-

Main Indications for $TcCO_2$ Monitoring

Neonatal Intensive Care Unit (NICU)

Assessment of hypoventilation
Titration of ventilation
Weaning

Pulmonary and Sleep Medicine

Assessment of (nocturnal) Hypoventilation

Titration of NIV

General Anesthesia / procedural sedation / surgery

Non conventional ventilation e.g. JET or High Frequency Ventilation

Indicator for OIRD

Homecare

Detection of nocturnal hypoventilation
Data download and sent to MD

Post Anesthesia Care Unit (PACU)

Assessment of hypoventilation
Indicator for opioid induced respiratory depression especially for high risk patients

Adult Critical Care

Guiding mechanical ventilation
Monitoring during weaning

Emergency Room

Assessment of hypoventilation

General Practice

Spot-check of ventilation

General Care Floor

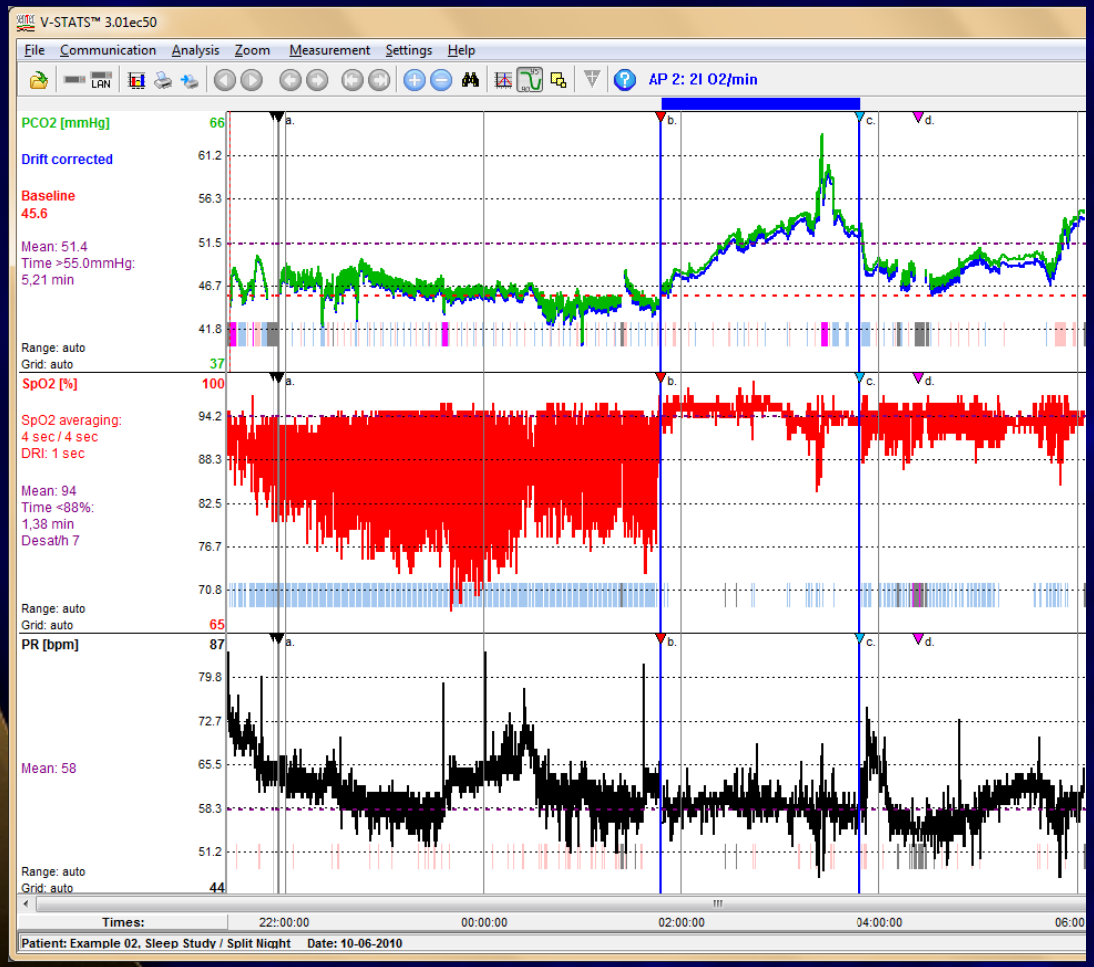
Assessment of hypoventilation

Main Indications for the $TcCO_2$

- Continuous monitoring or spot check measurements of ventilation ($tcPCO_2$) & oxygenation (SpO_2) in hospital or office settings, at home, or during transport
- Whenever $etCO_2$ is unreliable or difficult to use
- Mechanically Ventilated Patients
  - Invasive Ventilation (titrate ventilation, one-lung ventilation, HFOV, HFJV, SBT, weaning)
  - Noninvasive Ventilation (Initiate/ titrate NIV (helps to avoid intubation!),..)
- Spontaneously Breathing Patients
  - Sleep Medicine (Interfaced with PG/ PSG systems or as screening tool, OHS, ..)
  - Pain Management (Procedural Sedation, Recovery Room, General Care Floor)
  - Other Settings (Exercise Testing, Dialysis, …)

Sleep Studies

Titration of oxygen (Split night study) – patient with Cheyne-Stokes Breathing



Analysis Period 0 (AP 0) *corresponds to the Initial Phase (from the beginning to the first grey line)*

During Analysis Period 1 (AP 1) *the patient was breathing room air (from the first grey to the first blue line)*

During Analysis Period 2 (AP 2) *two liters of oxygen were administered (from the first to the second blue line)*

During Analysis Period 3 (AP 3) *one liter of oxygen was administered (from second blue line to end)*

Pain Management

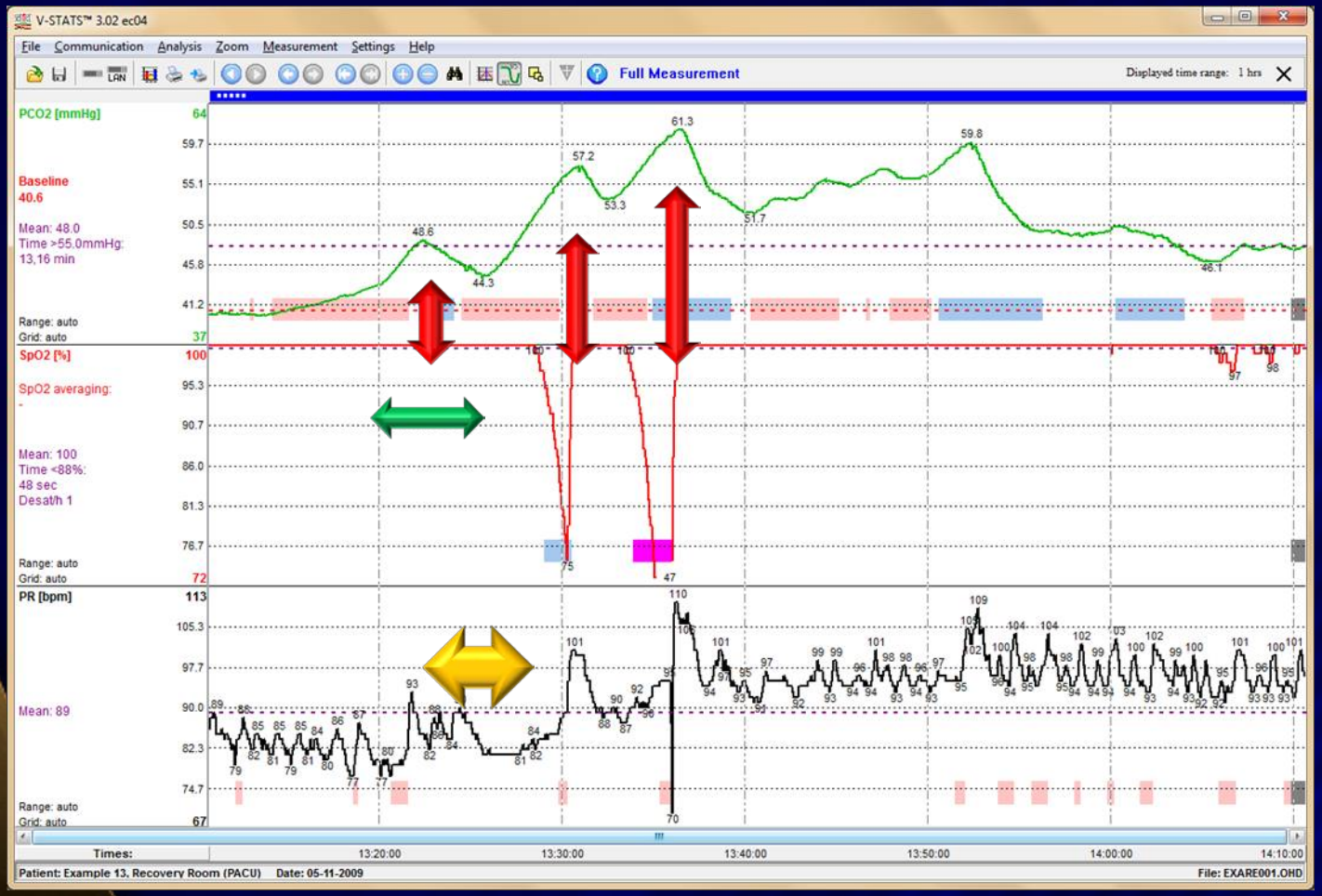
- In the recovery room (PACU) during the postoperative period.
- On the general care floor for patients receiving PCA
- During interventions performed under procedural sedation

Remember:

- ✓ Supplemental oxygen impairs detection of hypoventilation by SpO_2 whereas CO_2 monitoring unambiguously reflects hypoventilation irrespectively of supplemental oxygen being administered or not.
- ✓ This fact is especially important in spontaneously breathing patients in the above mentioned settings. Those patients, and in particular the sub-group of OSA and bariatric patients, are at increased risk to undergo OIRD and airway obstruction.
- ✓ $tcpCO_2$ monitoring in those settings helps to improve pain management and patient safety as it reliably reveals drug-induced hypoventilation in patients receiving supplemental oxygen!

Recovery Room – Post Limb Surgery

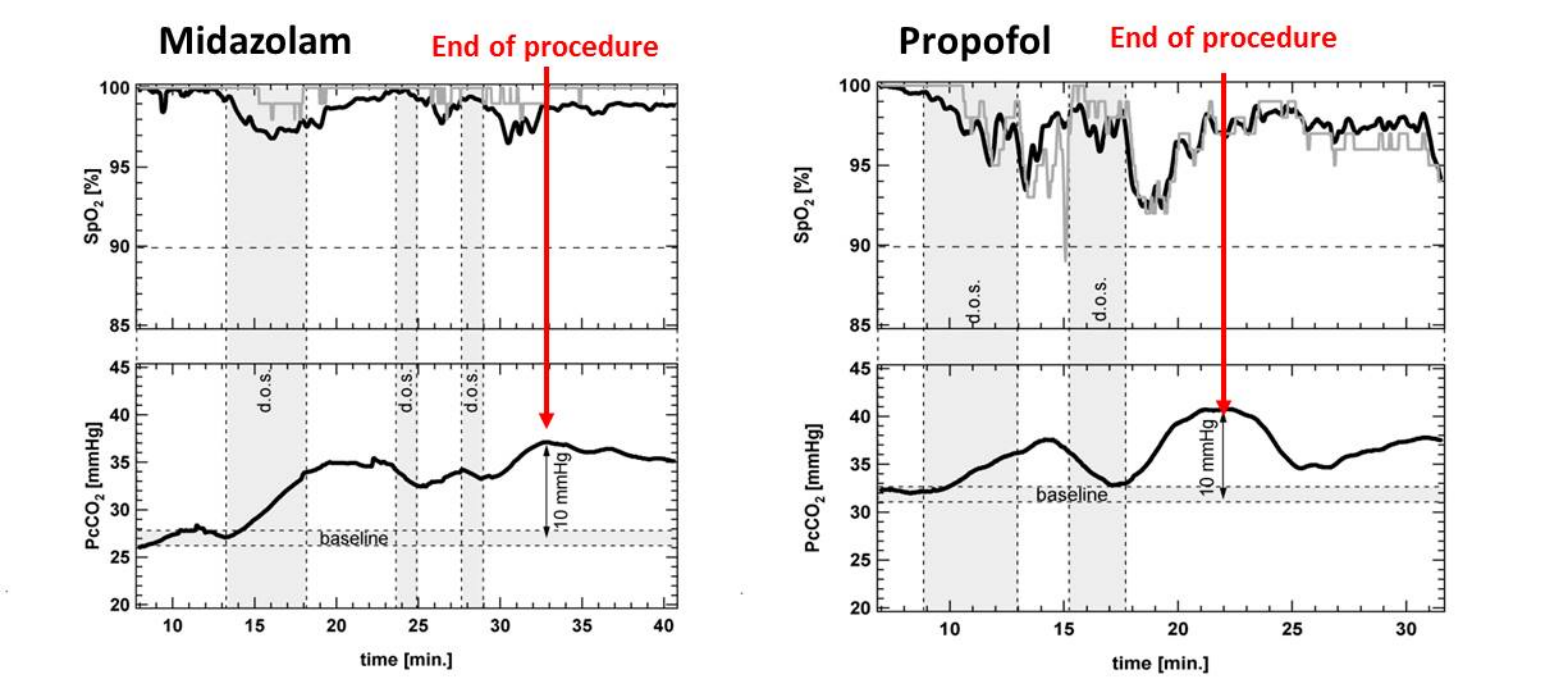
ASA 2, 4 L O_2/min



At red arrow significant $tcPCO_2$ raise above baseline, no desaturation

5 to 6 minutes later $tcPCO_2$ further raises, this time accompanied by pronounced desaturation

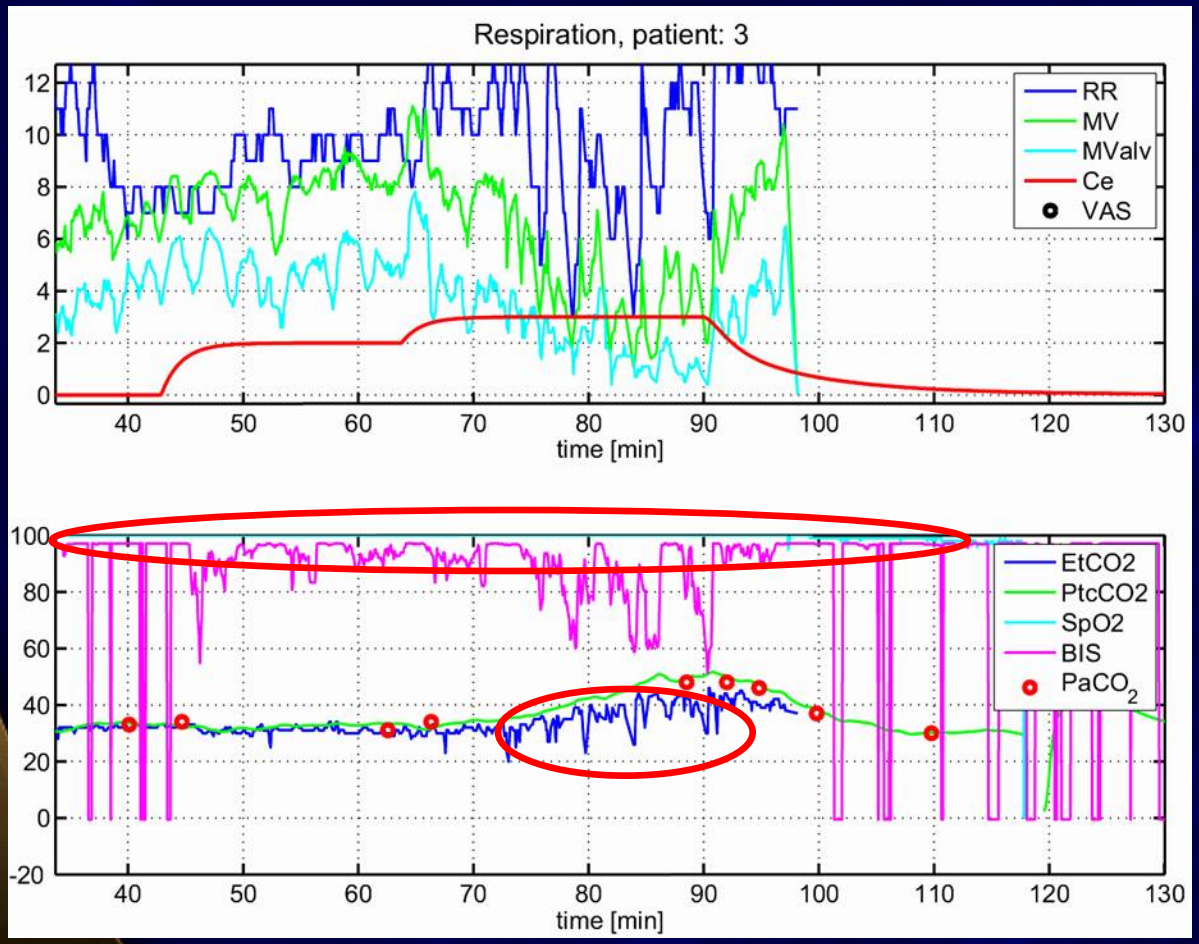
Conscious Sedation During Colonoscopy 1



- SpO_2 fails to detect hypoventilation when supplementary oxygen is administered
- Increase of PCO_2 reflects hypoventilation despite SpO_2 above 97%

Digestion 2004;70:152–158

Conscious Sedation During Colonoscopy 2



- two increasing levels of remifentanil
- profound respiratory depression (RR < 4, MV < 2 L/min)

- O_2 saturation stays at 100%
- unreliable Et CO_2 measurements

Schumacher et al. , unpublished data

Exercise Testing – COPD (Pre-transplant)

Drastic increase of PCO_2 during exercise

After exercise PCO_2 remains significantly above baseline

During Initiation of NIV

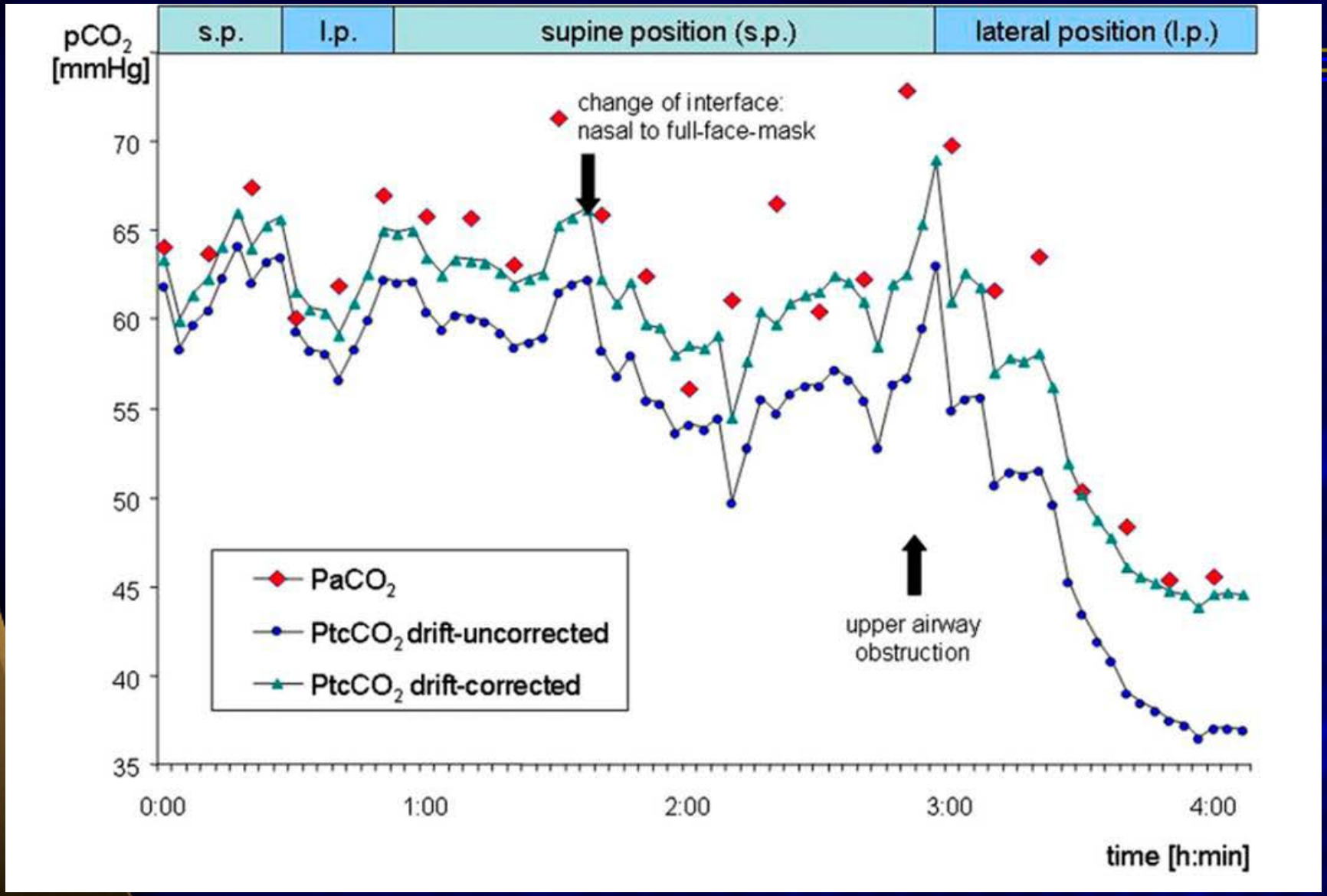
- $TcCO_2$ monitoring may adequately assess trending of PCO_2 in changing clinical scenarios [1-3]
  - Body position
  - Mask fitting
  - Sedation
- German guidelines recommend $PtcCO_2$ monitoring during acute NIV initiation, in addition to close-meshed ABG assessment.[4]

Storre JH, et al. Chest 2007;132:1810-1816.
Cox M, et al. Thorax 2006;61:363- 364.
Rodriguez P, et al. Intensive Care Med 2006;32:309-312.
Schonhofer B, et al. Deutsches Arzteblatt international 2008;105:424-433

During the Initiation of NIV

- $PetCO_2$ measurements might also provide information about trends in PCO_2, but may not be routinely recommended to monitor alveolar ventilation in
  - acute respiratory failure patients because of inaccurate readouts in patients with lung diseases, as well as those receiving NIV
  - in mechanically- ventilated infants and toddlers with acute respiratory failure
  - children with congenital heart disease
  - during interhospital transportation of critically ill patients
- $PtcCO_2$ monitoring is often reported superior to $PetCO_2$ monitoring in terms of accurately assessing alveolar ventilation.

Sanders MH, et al. Chest 1994;106:472-483
Wilson J, et al. J Intensive Care Med 2005;20:291-295.
Hinkelbein J, et al. J Trauma 2008;65:10-18.



Storre JH. Chest 2007;132:1810-1816.

Sleep

- Changes in alveolar ventilation during sleep of patients with CRF receiving NIV
  - sleep stages
  - body position
  - ventilation-perfusion mismatches
  - air leaks
- Using transcutaneous data advantageous versus $PetCO_2$.

Sleep

- SpO_2 and daytime ABG measurements are insufficient for the detection of nocturnal hypoventilation
  - in children on long–term NIV
  - in patients with neuromuscular diseases
- Combination of SpO_2 and $PtcCO_2$ monitoring has produced perfectly reliably results
- Better detection of nocturnal hypercapnia was also observed when $PtcCO_2$ was compared to CBG alone in adult patients receiving NIV

Neonatology

- Avoid hypo- or hypercapnia thereby helping to reduce the number of blood samples
- Hypocapnia (hyperverventilation) = vasoconstriction = decreases CBF and may cause adverse cerebral outcome. At values < 22.5 mmHg brain damage can occur within a few minutes.
- Hypercapnia = vasodilation = increase CBF = increase ICP = IVH

Sensor is safely set to 41°C making site inspections necessary as infrequently as every eight hours.

Other Applications

- **High-frequency Jet Ventilation (HFJV)**
  - $EtCO_2$ measurements are difficult or impossible
  - $tcpCO_2$ useful to adjust the driving pressure in the jet ventilator
- **One-lung Ventilation**
  - Impairs the perfusion/ventilation matching making $etCO_2$ a bad estimate for $PaCO_2$
- **Neurosurgery**
  - $tcpCO_2$ monitoring helps to prevent acute changes in cerebral blood flow shifts

Final Thoughts

1. PCO_2 monitoring is an important tool within a broad spectrum of clinical settings, most importantly in patients with respiratory failure that leads to hypercapnia.
2. Different methods have been developed for their clinical application in invasive (ABG, CBG and VBG) and non-invasive ($PtcCO_2$ and $PetCO_2$) measurements.
3. These techniques differ considerably with regard to their accuracy, capacity to facilitate continuous assessment, side effects, availability, and the capacity to assess additional information.
4. Each technique has its own spectrum of indications and applications.

Final Thoughts

5. The different techniques are not competitive but rather complementary
6. Specific clinical scenarios might require the combination of different techniques.
7. Transcutaneous PCO_2 monitoring seems to be the technique that is currently undergoing the most development.
8. TCM offers the opportunity to safely and routinely monitor alveolar hypoventilation, even outside the ICU during many clinical procedures.

THANK YOU