Non-Invasive CO_2 Monitoring: T ond

Departments of Anesthesiology & Pediatrics
Nationwide Children's Hospital
Columbus, Ohio

NATIONWIDE CHILDREN'S
When your child needs a hospital, everything matters.℠

OHIO STATE

Joseph.Tobias@Nationwidechildrens.org

- This presentation is supported by Sentec AG (Therwil, Switzerland).
- Sentec has supported my clinical research by providing me with a transcutaneous monitor and the disposable supplies for its use.
- No honorarium or proprietary interests.


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PRESS
RA/CVP
ARTERIAL
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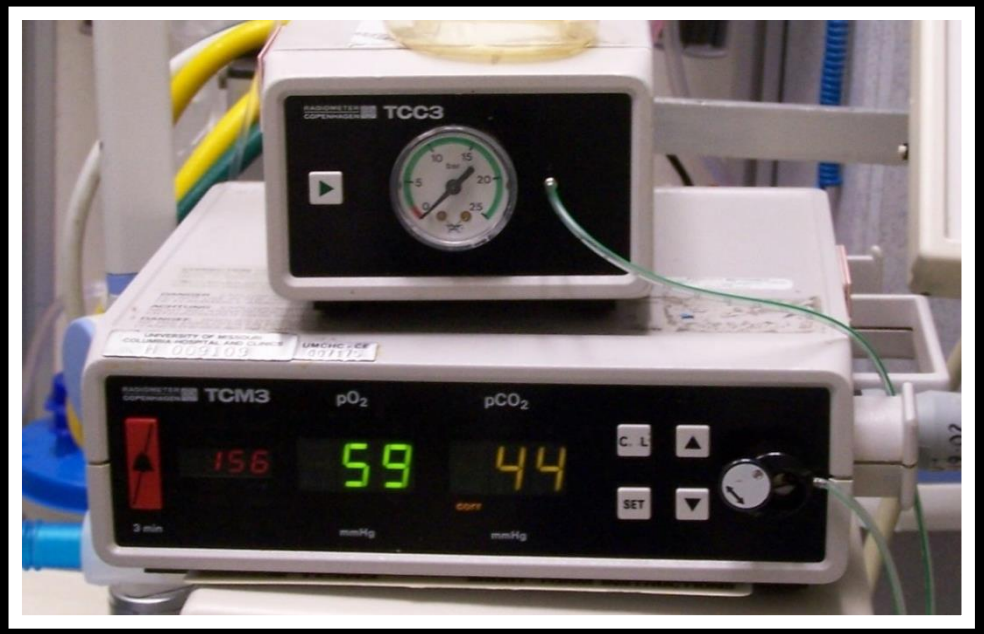
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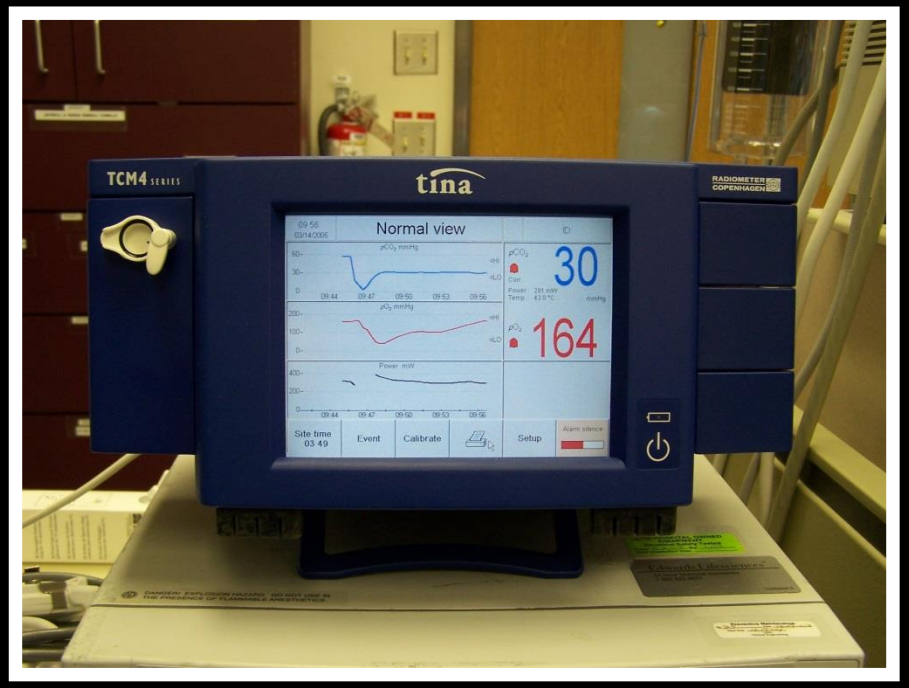
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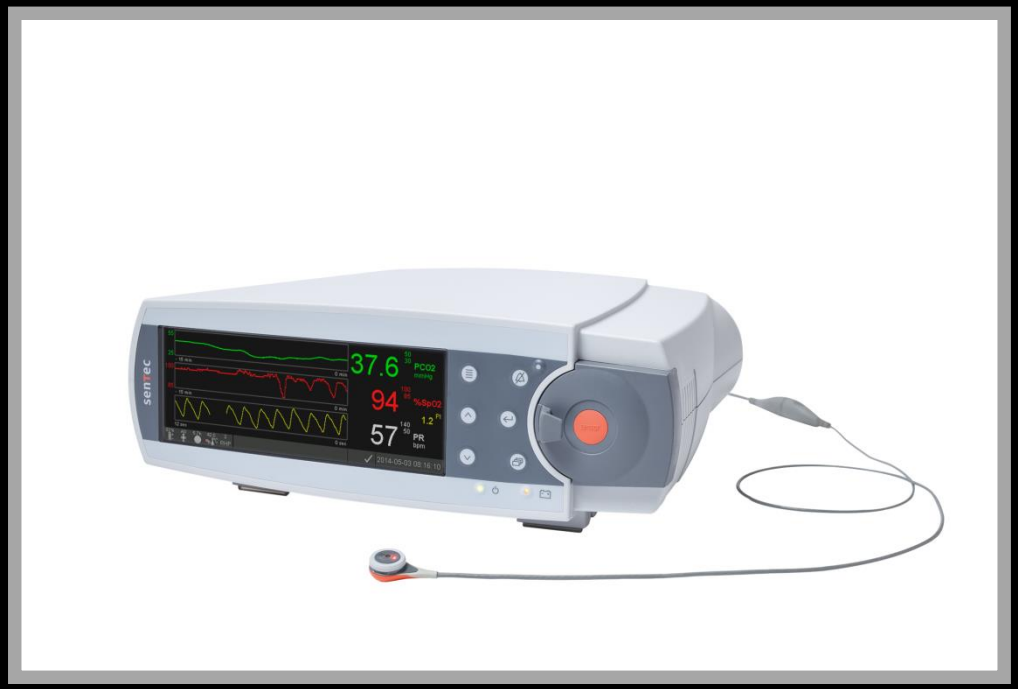
sen ec
37.6
PCO2
94
%SpO2
57
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bpm

Transcutaneous CO_2 Monitoring

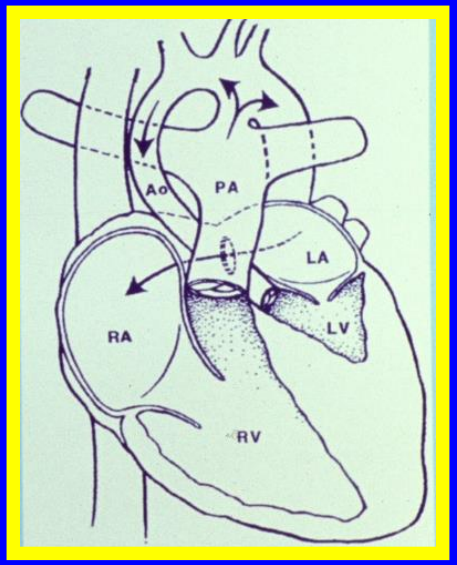
- ***the need for continuous CO_2 monitoring***
- venous or capillary vs. arterial values
- methods of continuous non-invasive CO_2 monitoring
- applications of transcutaneous CO_2 monitoring

Continuous P_{CO2} Monitoring

- clinical assessment is inaccurate
  - gold standard for P_{CO2} monitoring is ABG analysis
- ABG analysis
  - instantaneous value for a continuously changing clinical picture
  - may not be immediately available
    - transport, remote locations, outlying ED's
  - requires an invasive procedure
  - not immediately available without indwelling catheter
  - crying during procedure may alter results
  - cost: drawing sample + running test
- consequences of invasive procedure
  - pain and physiologic stress
  - risk of morbidity from indwelling catheter
  - does my patient really need an arterial line – will it last?
  - repeated phlebotomy

My Patient Needs Normocarbia

- cardiovascular dysfunction
  - hypercarbia & acidosis impair myocardial performance
- closed head injury
  - hyperventilation results in less favorable outcome
  - hypercarbia increases ICP
- neonates
  - alterations in $PaCO_2$ and CBF may → ICH
- congenital heart disease
  - infants with single ventricle physiology
  - pulmonary hypertension



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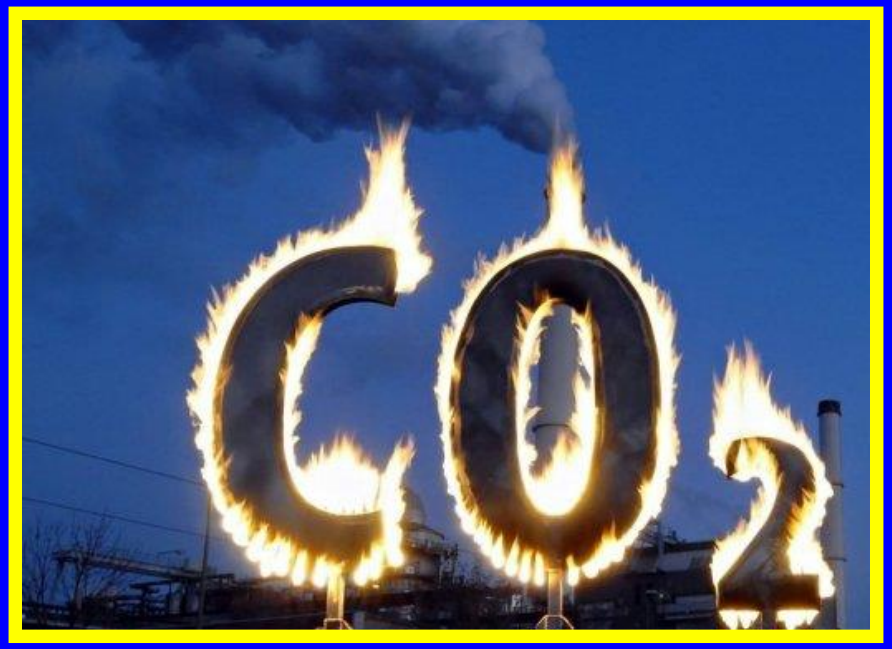


CBG vs. ABG Values

Escalanet-Kanashiro R et al, *Crit Care Med* 2000;28:224

- prospective trial in 75 pediatric patients
  - paired sample (CBG versus ABG)
  - perfusion, hemodynamics, blood pressure, temperature
- differences between the mean values
  - P_{CO2} = 0.44 mmHg
  - pH = 0
  - P_{O2} = 51 mmHg
- correlation for P_{CO2}
  - no hypotension = 0.86
  - hypotension = 0.52

VBG vs. ABG Values

Inoue T et al, *Cardiology* 1993;82:383

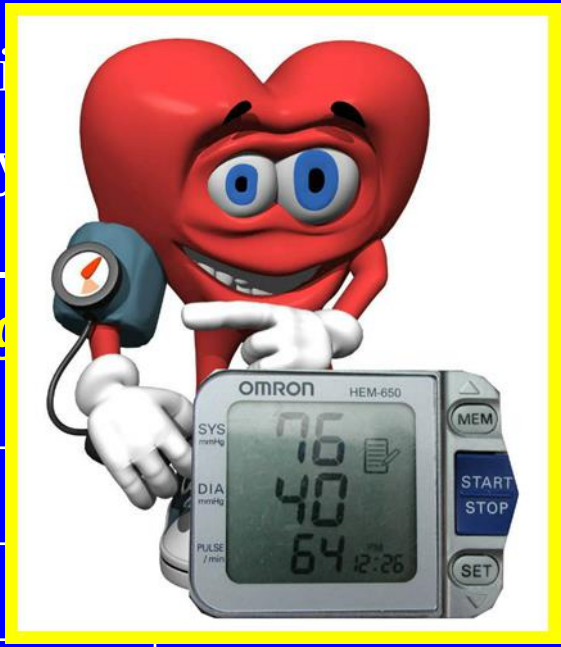
- VBG vs. ABG values in adults
- 7 with CHF versus 10 without CHF

	CHF patients	*controls*	*P value*
CI ($L/min/m^2$)	2.2 ± 0.2	3.1 ± 0.6	<0.01
PCWP (mmHg)	24 ± 5	10 ± 4	<0.001
SaO_2	97 ± 2	97 ± 1	NS
SvO_2	53 ± 12	75 ± 13	<0.001
$P(v\text{-}a)CO_2$ (mmHg)	7.8 ± 2.6	3.5 ± 2.2	<0.01
$PvCO_2$ (mmHg)	50 ± 5	40 ± 5	<0.01
$PaCO_2$ (mmHg)	41 ± 8	39 ± 5	NS

VBG vs. ABG Values

McBride ME et al, *J Intensive Care Med* 2001;16:231

- 14 infants and chi[illegible] othoracic surgery
- 95 simultaneously [illegible] BG values



Central venous oxyg[illegible] saturation (%)	*[illegible]l P_{CO2} difference [illegible]mHg)*
≥ 70	[illegible]5 ± 3.1
60-69.9	[illegible]0 ± 3.4*
50-59.9	9.9 ± 3.6*
< 50	10.7 ± 4.1*

*p<0.05 vs. ≥ 70% group

Arterial to Venous CO2 Gradient

A high arterial to venous CO_2 gradient at admission in the postoperative ICU was associated with increased postoperative complications in high-risk surgical patients.

Robin E et al, *Crit Care* 2015;19:227

269 samples from 139 infants. Patients with poor outcome had a venous to arterial CO_2 difference of 8.3 (5.6-14.9) versus 5.4 mmHg (3.0-8.4) in those without poor outcome.

Rhodes LA et al, *Ped Crit Care Med* 2017;18:228

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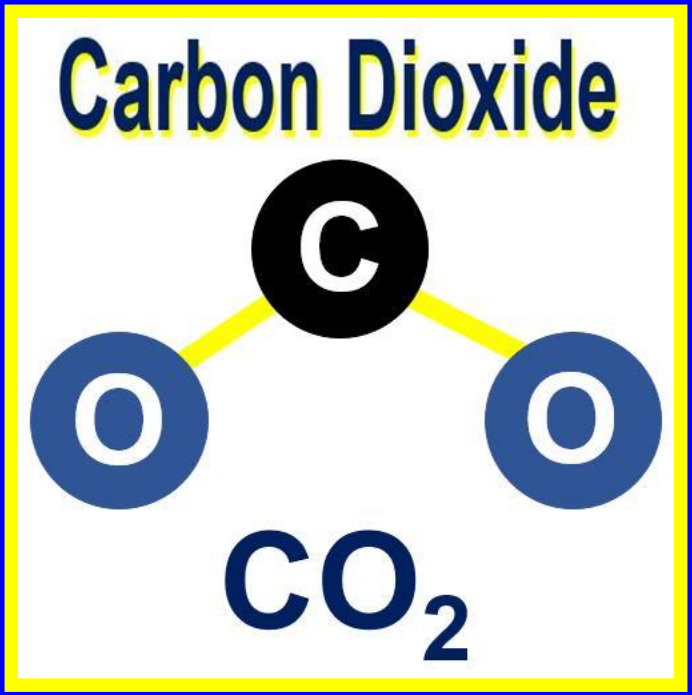
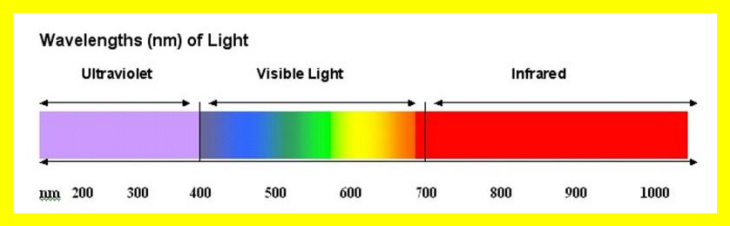
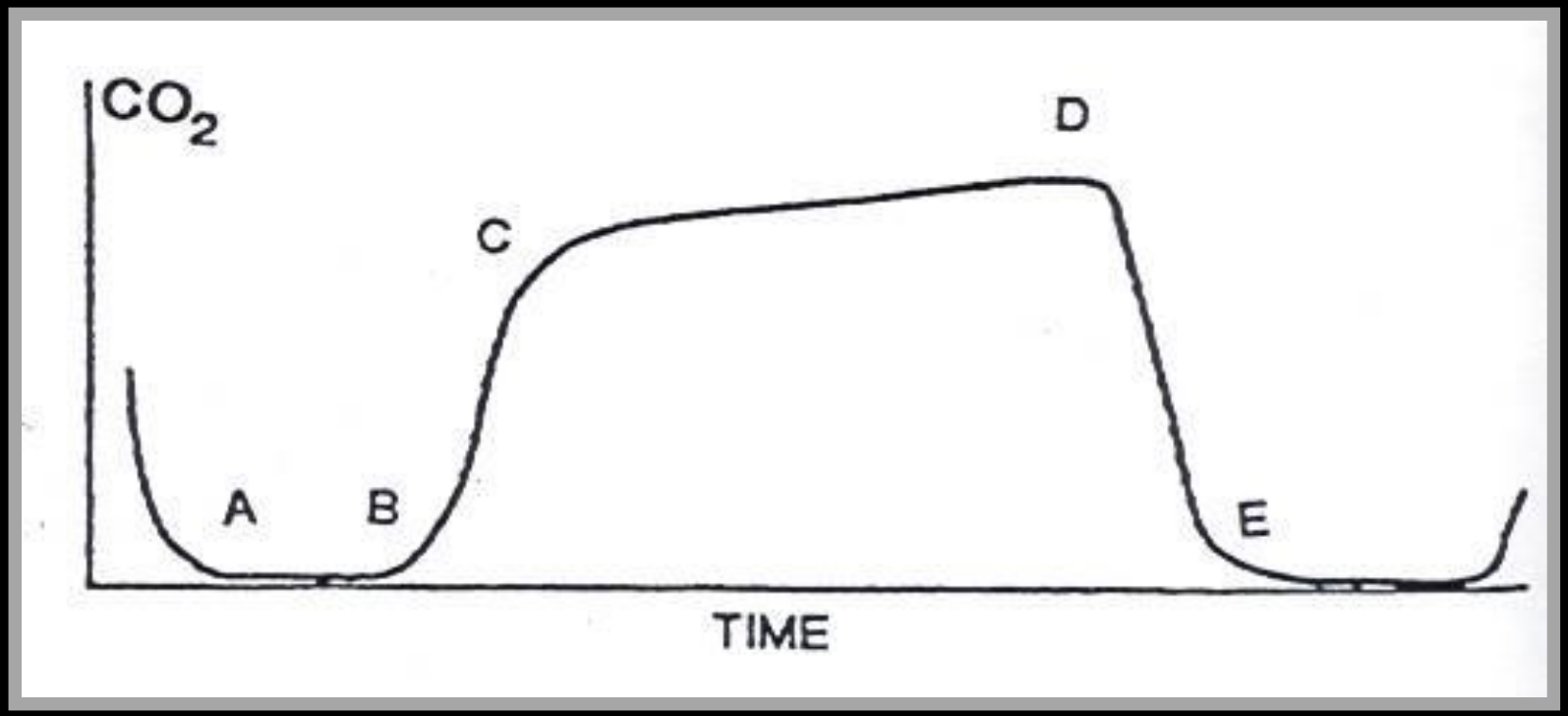


End-tidal CO_2 Monitoring



- infrared absorption
  - most common method
  - CO_2 absorbs infrared light
  - light passed through gas sample
  - compared to gas with known CO_2 concentration
- Raman spectroscopy
  - gas sample illuminated with laser beam
  - gas sample scatters the light and shifts frequency
- mass spectroscopy
  - expensive and cumbersome

The Capnogram

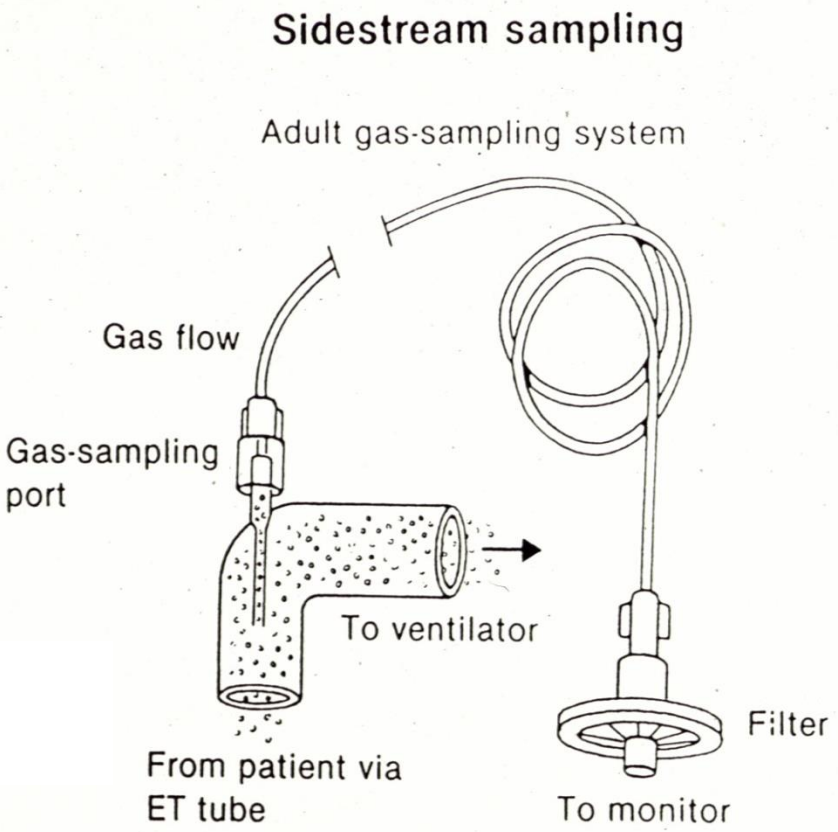


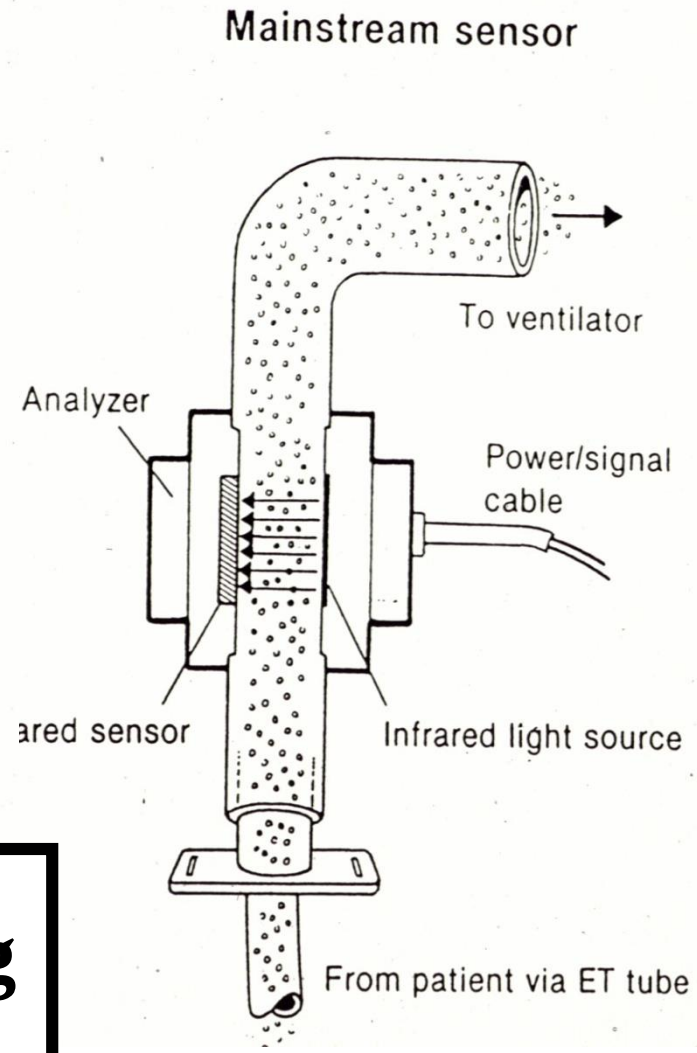
A-B: Initial phase of expiration, no CO_2 only gas from anatomic dead space

B-C: Start of alveolar emptying, upstroke determined by distribution of ventilation

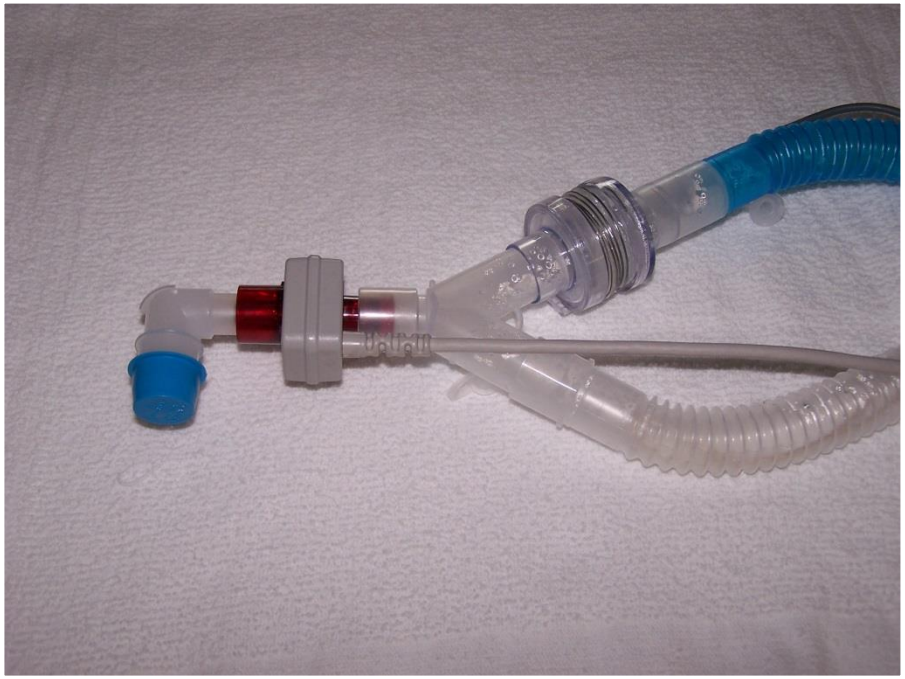
C-D: Alveolar or expiratory plateau, should be horizontal, point D is the highest CO_2 value ($ETCO_2$), best reflection of alveolar CO_2 and therefore arterial CO_2

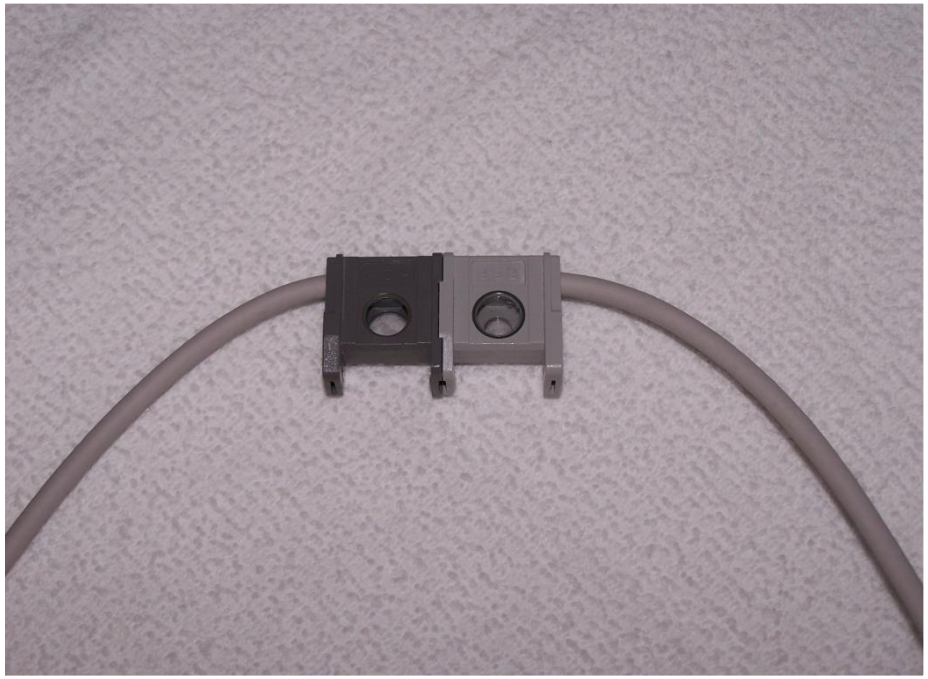
D-E: Inspiration begins, baseline should approach zero unless there is rebreathing

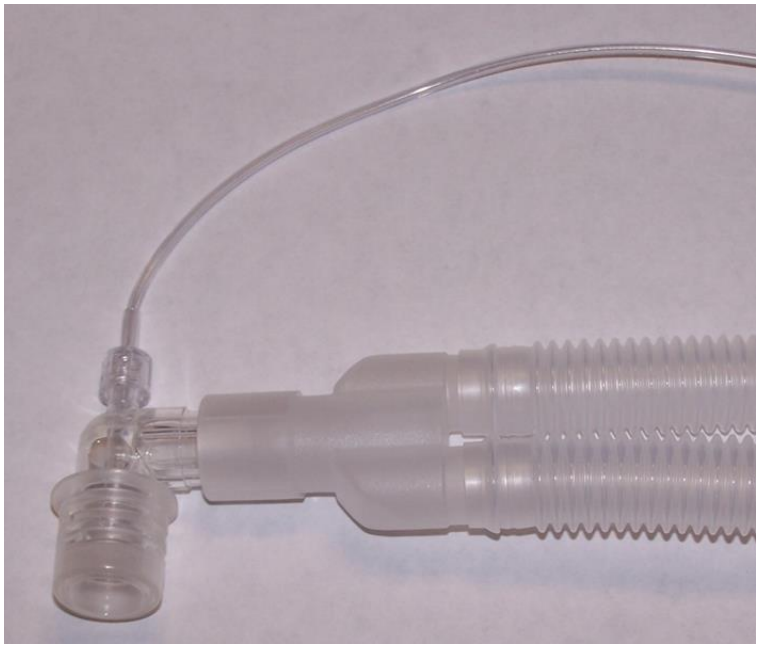


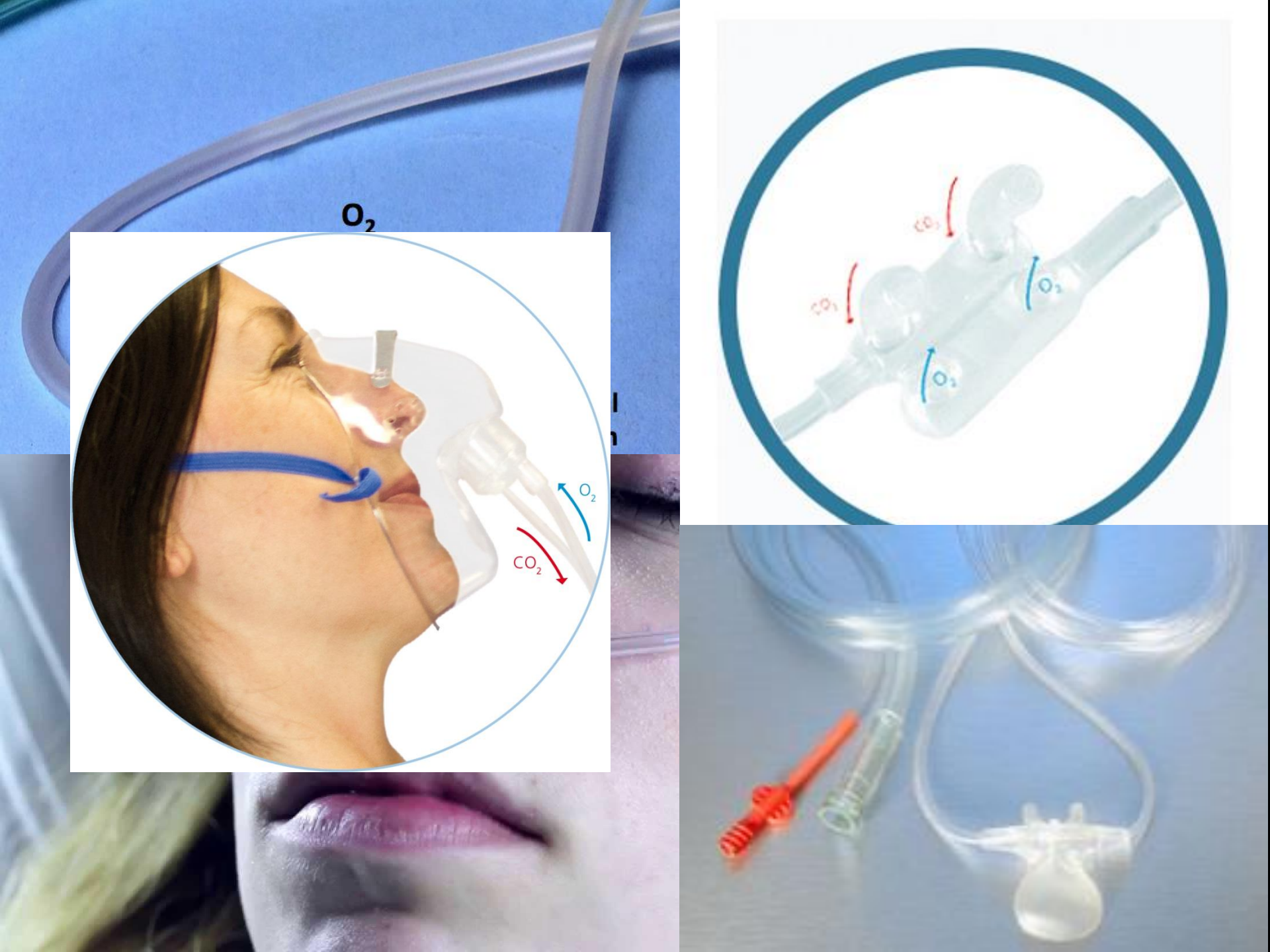


End-tidal CO_2 Monitoring








O_2
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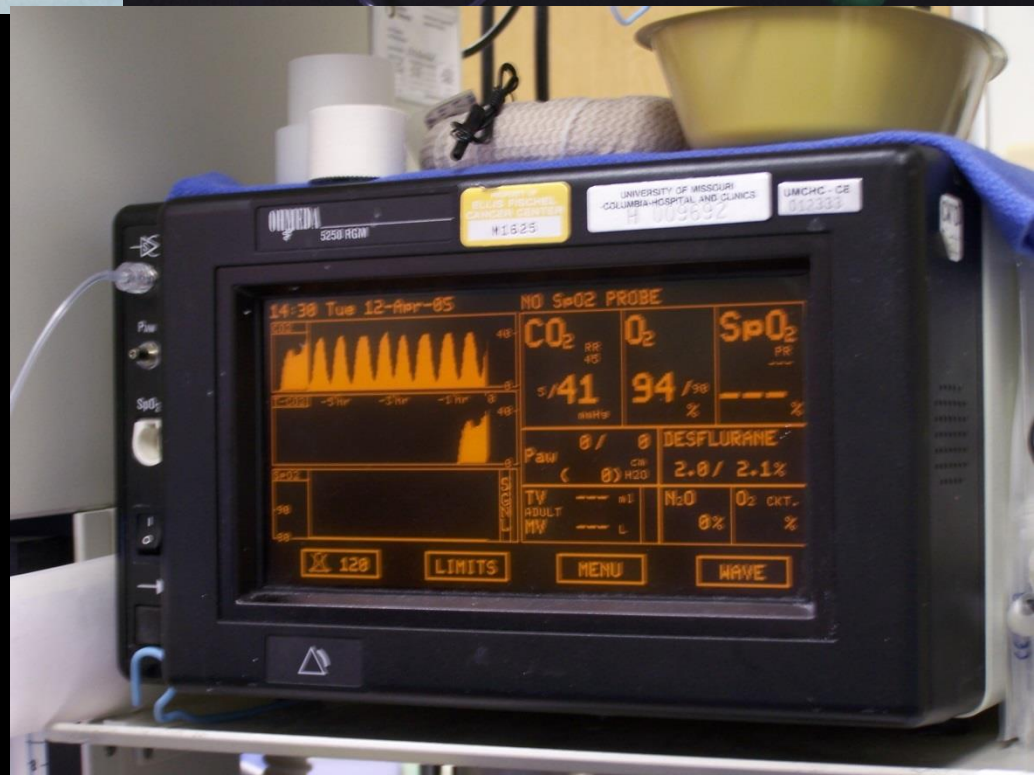
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UNIVERSITY OF MISSOURI
COLUMBIA HOSPITAL AND CLINICS
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NO SpO2 PROBE
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SpO2
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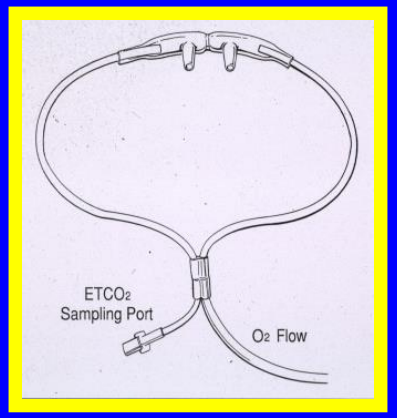
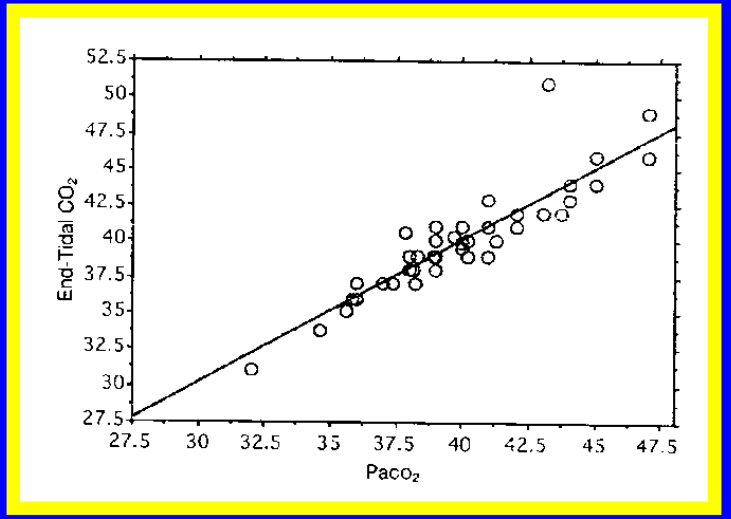
94
DESFLURANE
2.0/ 2.1%
N2O
0%
LIMITS
MENU
WAVE

$ETCO_2$: Extubated - Nasal Cannula

Tobias JD et al, *Crit Care Med* 1994;22:1805

- prospective trial in 30 pediatric patients
  - 6 months to 16 years (average = 7.8 years)
  - extubated, spontaneous ventilation
  - postoperative, no intrinsic lung disease
  - $ETCO_2$ monitor from nasal cannula
  - 55 sample sets
- $ETCO_2$ to $PaCO_2$ difference
  - 2.2 ± 0.9 mmHg
  - ≤ 4 mmHg in 54 of 55 samples
  - linear regression analysis





End-tidal CO_2 Monitoring

- easy to set-up and use, limited calibration time
- reflects $PaCO_2$ with normal pulmonary function
- documents intra-tracheal position of ETT
  - standard of care for intraoperative monitoring
  - standard of care for ET intubation anywhere
  - Standard of care for sedation monitoring???
- documents ongoing ETT placement
  - transport, ICU, OR (disconnect monitor)
- waveform provides → pulmonary function information
- demonstrates efficacy of CPR

Accuracy of $ETCO_2$ Monitoring

- normal ventilation-perfusion ratio
- alveolar CO_2 must correlate with arterial CO_2
  - patient positioning
  - decreased FRC
  - alveolar space disease → V/Q mismatch
  - decreased pulmonary blood flow
  - increased dead space
  - shunt (cyanotic congenital heart disease)
- sampling issues
  - small tidal volumes
  - rapid respiratory rates
  - sampling site
  - continuous gas flow ventilators

Accuracy of $ETCO_2$ Monitoring

$ETCO_2$ accuracy questionable during one-lung ventilation
Yam PCI et al, *Br J Anaesth* 1994;72:21

$ETCO_2$ inaccurate in infants with CHD
Short JA et al, *Br J Anaesth* 2001;86:349
Burrows FA, *Anesthesiology* 1989;70:219

Patient positioning affects accuracy of $ETCO_2$ monitoring
Panard JL et al, *Anesth Analg* 1992;75:506
Grenier B et al, *Anesth Analg* 1999;88:43

Site of sampling affects accuracy of $ETCO_2$ monitoring
Hillier SC et al, *Can J Anaesth* 1990;37:318

Type of ventilator affects accuracy of $ETCO_2$ monitoring
Badgwell JM et al, *Anesthesiology* 1987;66:405

$ETCO_2$ changes based on deadspace ventilation
Yamanaka MK et al, *Chest* 1987;92:832

$ETCO_2$ does not reflect $PaCO_2$ in critically ill adult ICU patients
Hoffman RA et al, *Amer Rev Resp Dis* 1989;140:1265

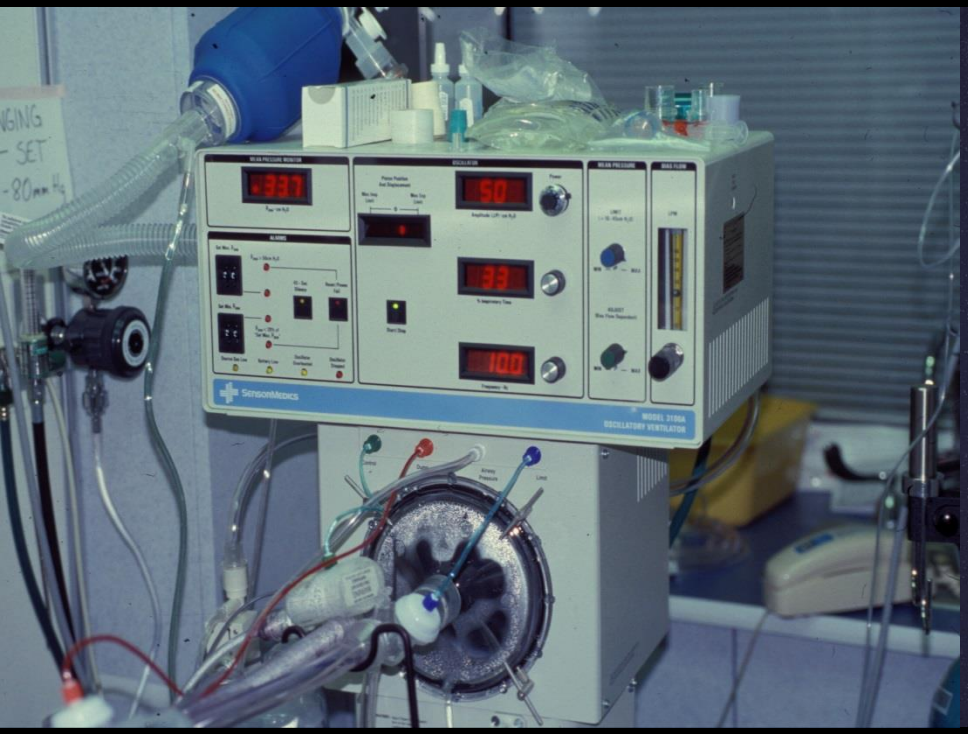
$ETCO_2$ does not reflect $PaCO_2$ during intraoperative care
Wahaba RWM et al, *Can J Anaesth* 1996;43:862

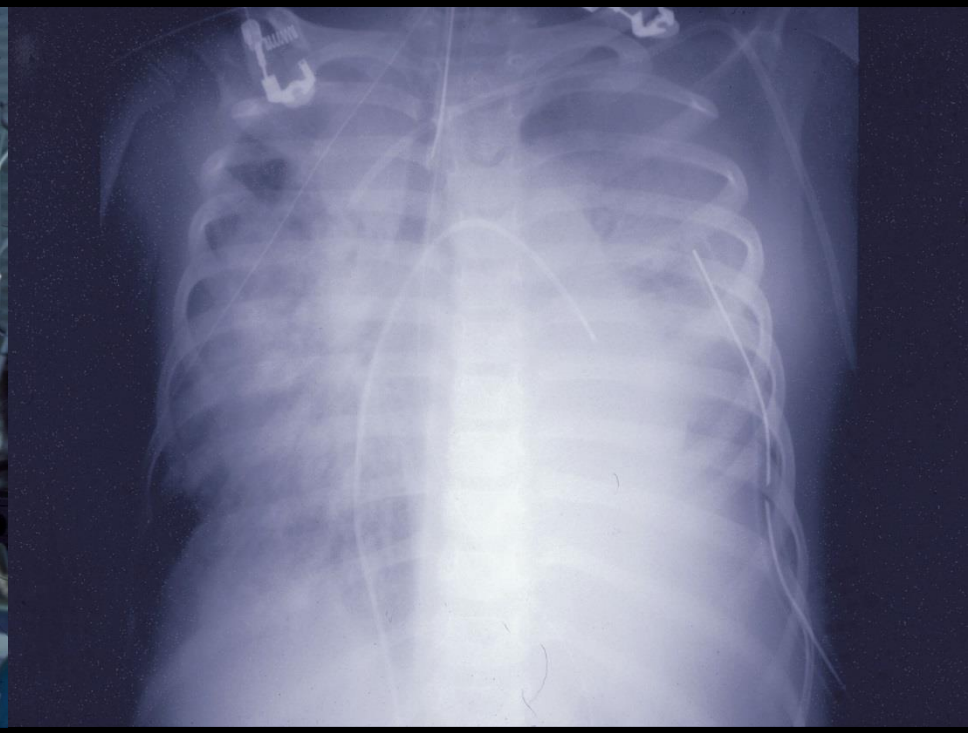
$ETCO_2$ is an essential monitoring device in the operating room and beyond.

It works well in patients with normal pulmonary function.

However, several factors may affect its accuracy or clinical scenarios may preclude its use.

Additionally, there may be situations in both the operating room and the ICU where $ETCO_2$ monitoring is not feasible.



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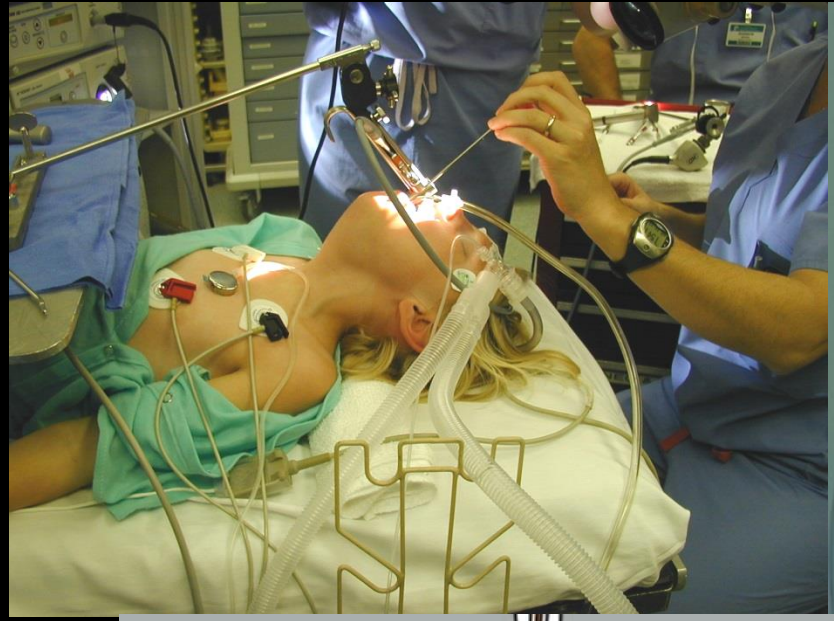
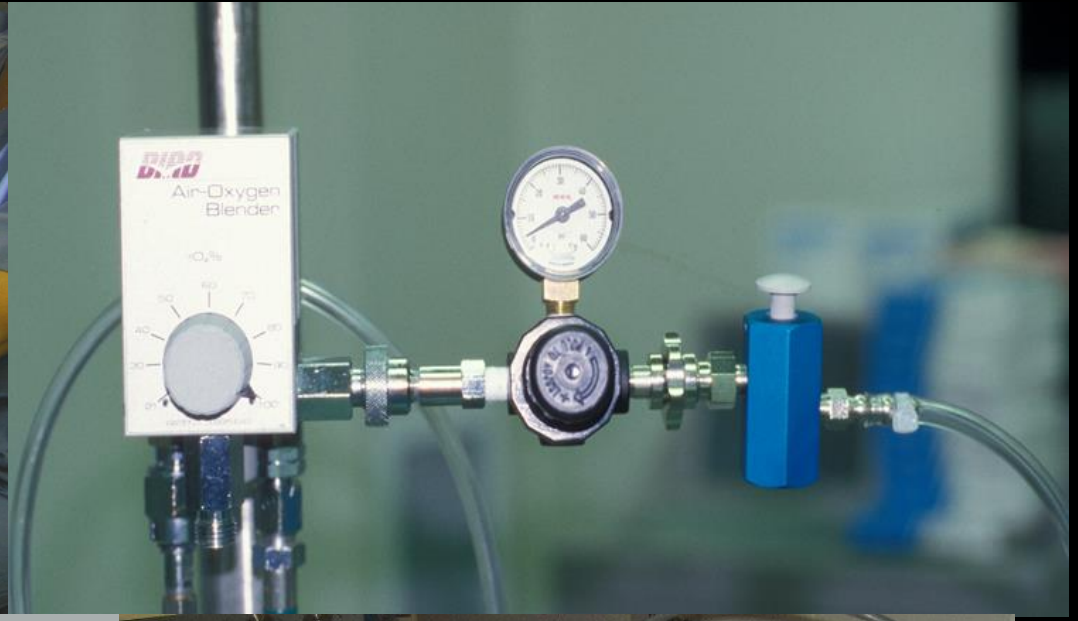
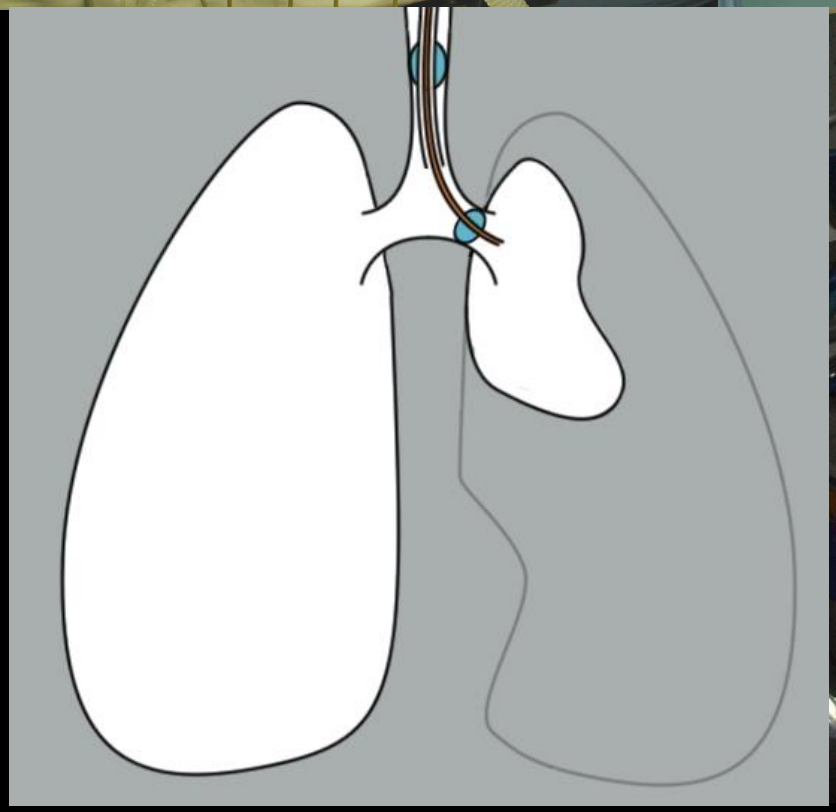



Air-Oxygen
Blender




MONITOR
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JET VALVE
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27.4
SERVO PRESS
2.1
PEEP
8.7
MAP
13.3
ALARMS
RESET
SILENCE
CONTROLS
PIP
NOW
32.
NEW
32.
RATE
420
420
on
.020
.020
JET VALVE TIME
on/off
1-6.1
ENTER
STANDBY
TEST
LIFE PULSE
ON
HIGH FREQUENCY VENTILATOR
HUMIDIFIER
TEMPERATURE
39.9
ALARMS
SILENCE
GAS OUT
bunnell
PURGE

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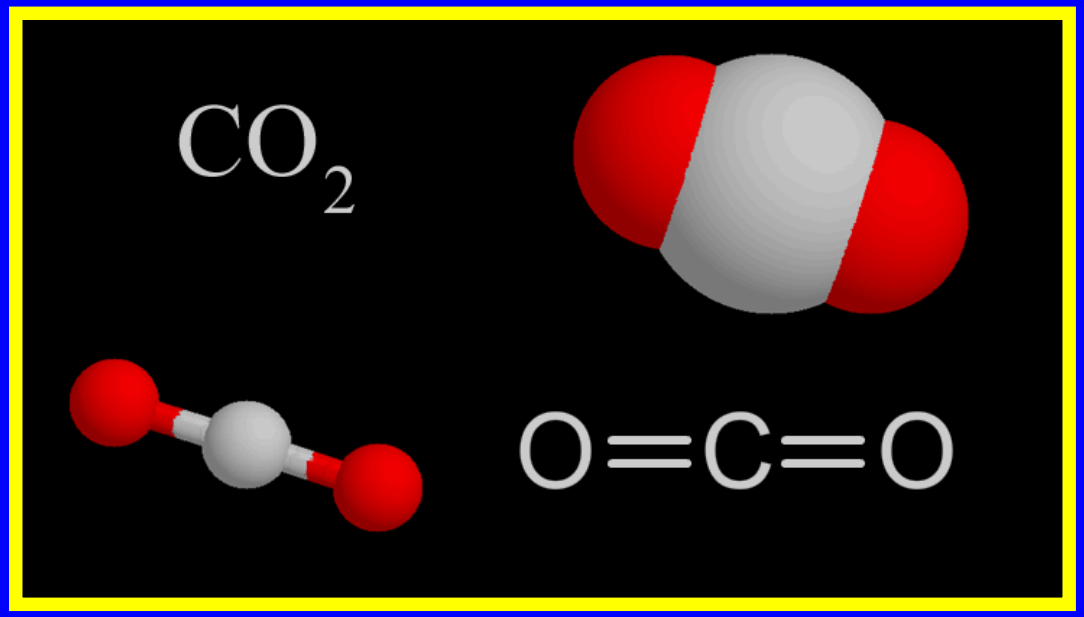
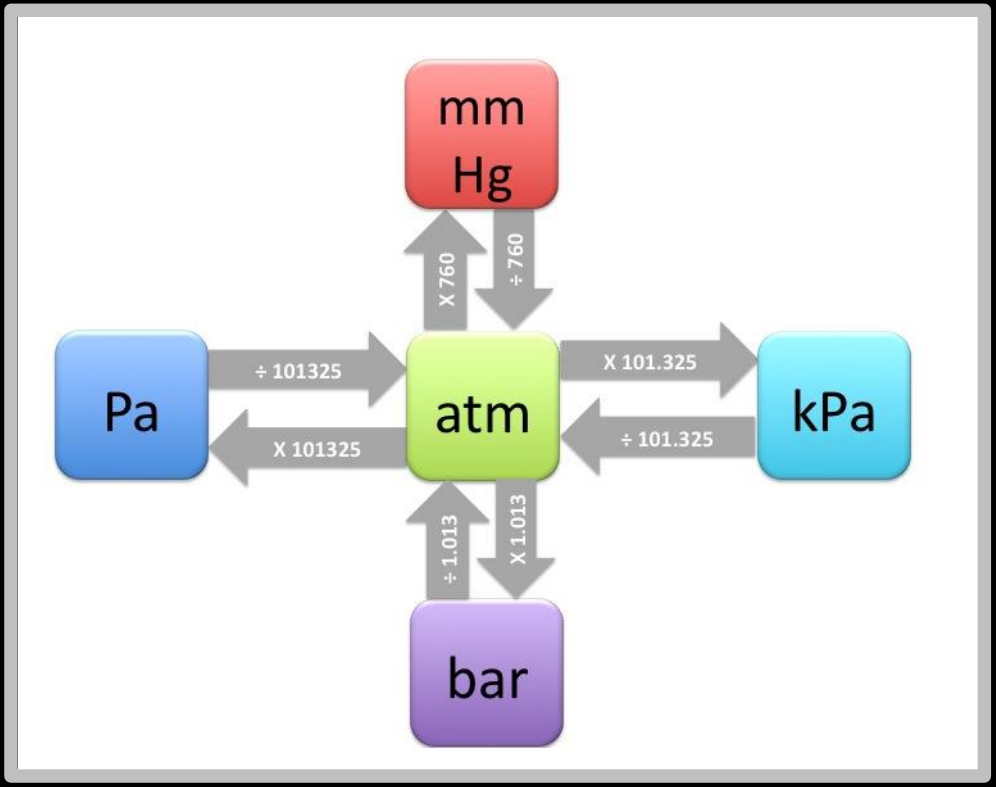


Units for blood gas results:
1 kPa = 7.5 mmHg



MIZZOU

UNIVERSITY OF MISSOURI SCHOOL OF MEDICINE
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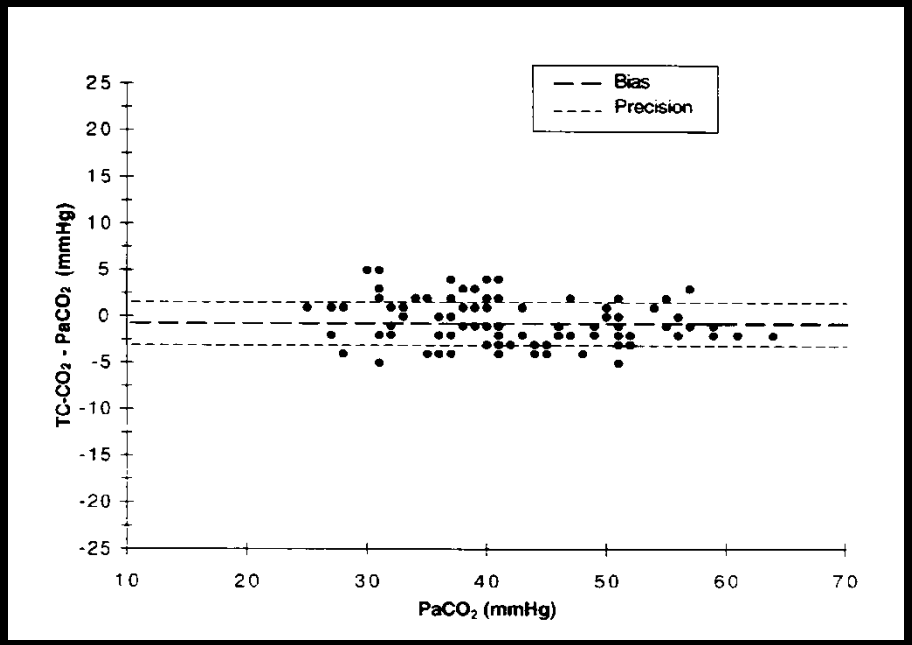
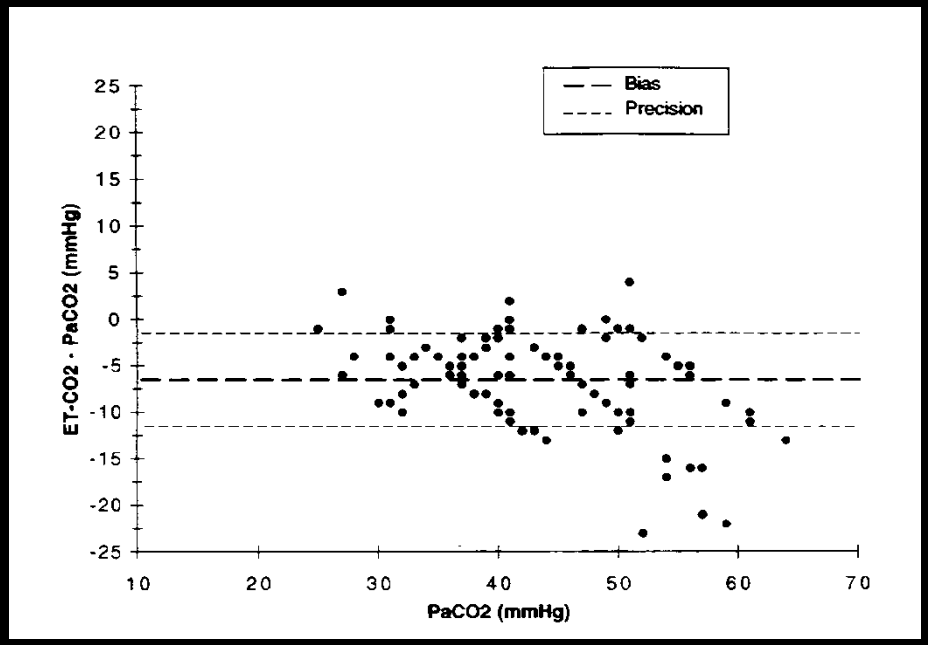
TC-CO_2 Monitoring: Pediatric ICU

Tobias JD et al, *Anesth Analg* 1997;85:55

- prospective study, 35 infants & toddlers, respiratory failure
  - 1 to 40 months of age, 3.3 to 19.1 kgs, mechanical ventilation
  - TC and ET CO_2 compared to $PaCO_2$
  - 100 paired samples sets (TC, ET and $PaCO_2$)

	TC-CO_2	***ET-CO_2***	***P value***
Difference from $PaCO_2$ (mmHg)	2.3 ± 1.3	6.8 ± 5.1	<0.0001
≤ 4 mmHg from $PaCO_2$	96 of 100	38 of 100	<0.0001





Tobias JD et al, *Anesth Analg* 1997;85:55

TC-CO_2 Monitoring: Pediatric ICU

Berkenbosch JW et al, *Anesth Analg* 2001;92:1427

- prospective study, 25 children, ≥ 4 years of age
  - mechanical ventilation
  - TC and ET CO_2 compared to $PaCO_2$
  - 82 paired samples sets (TC, ET and $PaCO_2$)

	TC-CO_2	***ET-CO_2***	***P value***
Difference from $PaCO_2$ (mmHg)	2.6 ± 2.0	6.4 ± 6.3	<0.0001
≤ 3 mmHg from $PaCO_2$	65 of 82	34 of 82	<0.0001
≤ 5 mmHg from $PaCO_2$	76 of 82	47 of 82	<0.0001
Linear regression analysis, r value	0.9693	0.8745	<0.05

TC-CO_2 Monitoring: Pediatric ICU

Berkenbosch JW et al, *Anesth Analg* 2001;92:1427

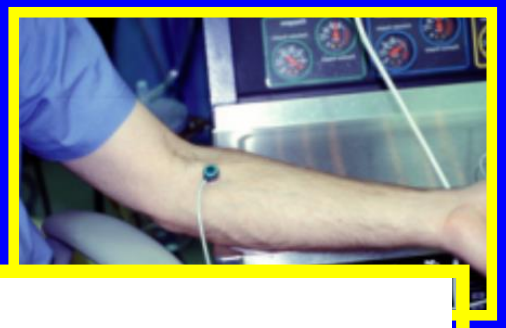
- prospective study, 14 patients
  - 1 day to 16 years of age
  - high frequency oscillatory ventilation
  - 100 paired samples sets (TC-CO_2 versus $PaCO_2$)

	TC-CO_2
Difference from $PaCO_2$ (mmHg)	2.8 ± 1.9
0-2 mmHg from $PaCO_2$	51 of 100
3-5 mmHg from $PaCO_2$	41 of 100
> 5 mmHg from $PaCO_2$	8 of 100
Linear regression analysis, r value	0.960
Difference with $PaCO_2 \leq 50$ mmHg (n=52)	1.9 ± 2.8
Difference with $PaCO_2 > 50$ mmHg (n=48)	2.3 ± 2.6

TC-CO_2: Gastric Bypass Surgery

Griffin J et al, *Br J Anaesth* 2003;91:498

- prospective study, 30 adults, BMI ≥ 40 kg/m^2
  - TC and ET-CO_2 compared to $PaCO_2$
  - 1 kPa = 7.5 mmHg



J Clin Monit Comput (2015) 29:183–186
DOI 10.1007/s10877-014-9587-1

ORIGINAL RESEARCH

Carbon dioxide monitoring during laparoscopic-assisted bariatric surgery in severely obese patients: transcutaneous versus end-tidal techniques

Joanna M. Dion · Chris McKee · Joseph D. Tobias · Daniel Herz · Paul Sohner · Steven Teich · Marc Michalsky

TC-CO_2: Following Cardiac Surgery

Tobias JD al, *Anesth Analg* 1999;88:531

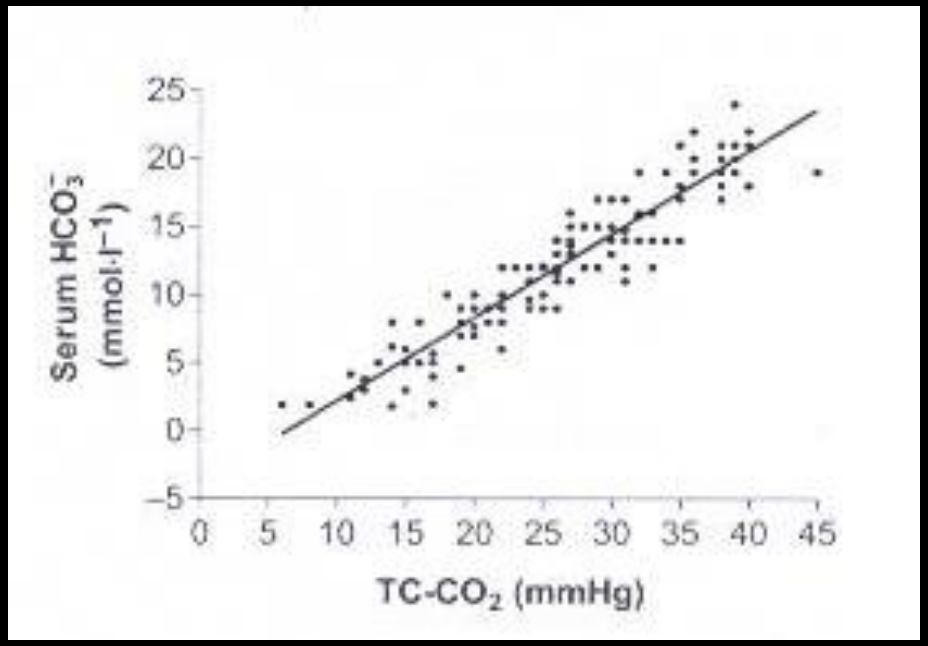
- prospective study, 30 infants & children, cardiac surgery
  - TC-CO_2 placed if initial Pa-ET CO_2 gradient ≥ 5 mmHg
  - 3 TC-CO_2 failures (cardiovascular instability)
    - dopamine 20 μg/kg/min + epinephrine 0.3-0.5 μg/kg/min
- study cohort (27 patients, 2 days to 9 years old)
  - 101 sample sets
- surgical procedure
  - thoracotomy, closed heart, open heart with bypass
- vasoactive medications
  - dopamine μg/kg/min: 0-5 (n=7), 6-10 (n=3), ≥ 11 (n=1)
  - dobutamine μg/kg/min: 0-5 (n=8), 6-10 (n=5), ≥ 11 (n=1)
  - milrinone μg/kg/min: 0.3-1 (n=6)
  - nicardipine (n=1), nitroglycerin (n=1)

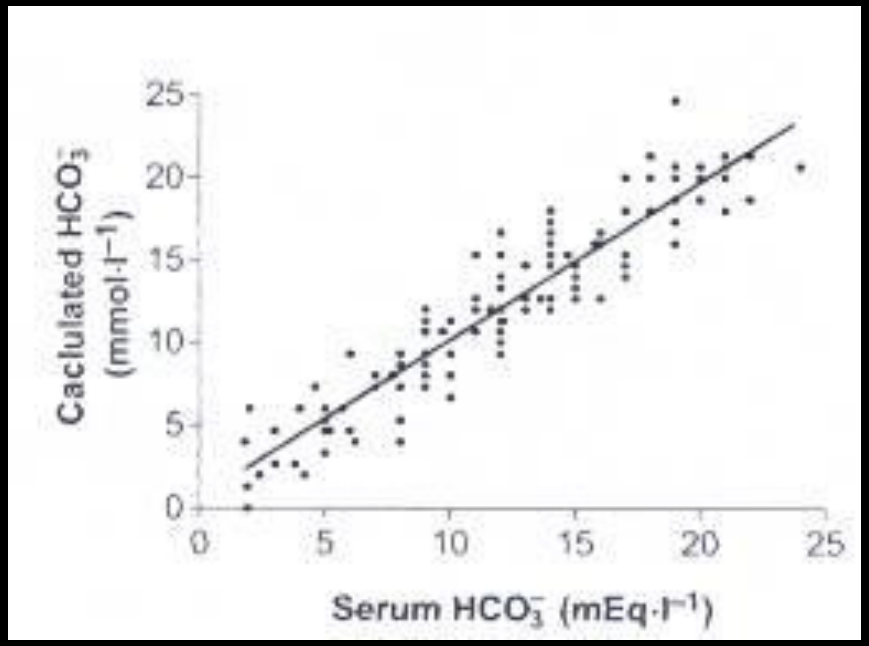
	TC-CO_2
Difference from $PaCO_2$ (mmHg)	1.7 ± 1.4
0-2 mmHg from $PaCO_2$	82 of 101
3-5 mmHg from $PaCO_2$	18 of 101
Linear regression analysis, r value	0.9410

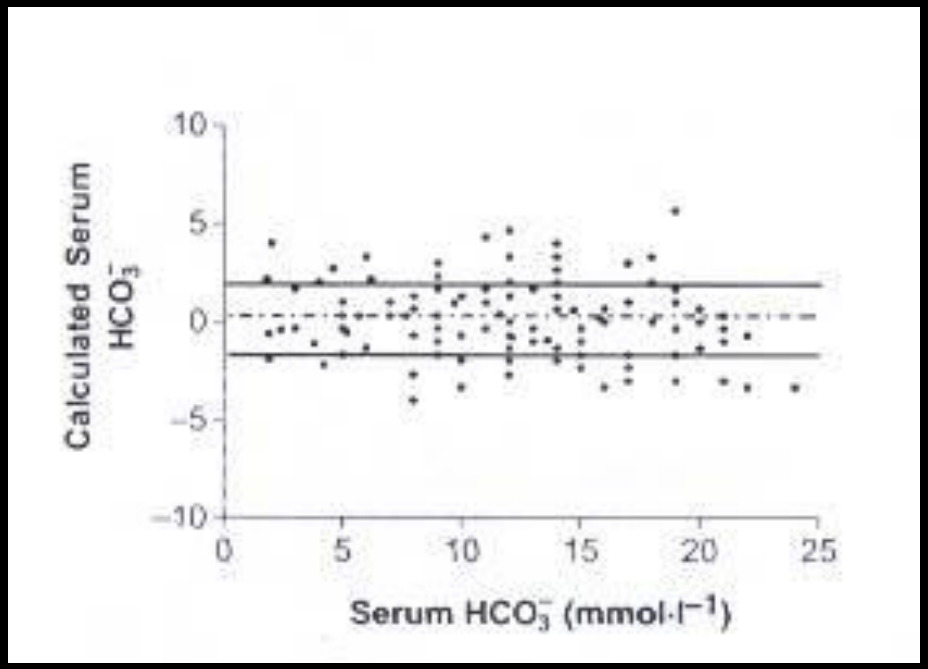
TC-CO_2 Monitoring: Pediatric ICU

McBride ME et al, *Pediatr Anesth* 2004;14:167

- DKA results in hyperventilation
  - compensates for metabolic acidosis
- hyperventilation → ↓ $PaCO_2$
- may be correlation between $PaCO_2$ and acidosis
- prospective study in 28 pediatric patients with DKA
  - 1.6 to 21 years, 13 to 96 kgs
  - TC-CO_2 monitoring during therapy
  - calculated vs. actual serum bicarbonate values
    - $PaCO_2 = (1.5 \times HCO_3) + 8$







Serum bicarbonate (HCO_3) = 0.61 x ($TCCO_2$ – 3.9)

TC-CO_2 Monitoring: Apnea Testing

Tobias JD, *J Intensive Care Med* 2001;16:76

- brain death examination prior to organ donation
- apnea testing
  - no respiratory effort with $PaCO_2 \geq 60$ mmHg
- TC-CO_2 monitoring during apnea test
  - used to guide timing of ABG analysis
  - 8 patients, 1 to 16 years of age
  - patients 1 & 2, ABG obtained with TC-CO_2 = 60 mmHg
    - PaCO2 < 60 mmHg in both cases
  - ABG obtained with TC-CO_2 = 70 mmHg
    - 15 of 16, $PaCO_2$ > 60 mmHg
    - TC-$PaCO_2$ difference (2-11 mmHg, 5.8 ± 2.7 mmHg)

Anesthesiology 2006; 104:701–7

An Evaluation of Transcutaneous Carbon Dioxide Partial Pressure Monitoring during Apnea Testing in Brain-dead Patients

Benoît Vivien, M.D., Ph.D., Frédéric Marmion, M.D.,* Sabine Roche, M.D.,* Catherine Devilliers, Sc.D.,† Olivier Langeron, M.D., Ph.D.,* Pierre Coriat, M.D.,‡ Bruno Riou, M.D., Ph.D.§*

Results: **In the first 20 patients, the mean $Paco_2$–$Ptcco_2$ gradient was 0.7 ± 3.6 mmHg at baseline and 8.7 ± 7.1 mmHg after 20 min of apnea. Using receiver operating characteristic curve analysis (area under the curve: 0.983 ± 0.013), the best threshold value of $Ptcco_2$ to predict that a $Paco_2$ of 60 mmHg had been reached was 60 mmHg (positive predictive value: 1.00 [0.93–1.00]). In the following 12 patients investigated with use of this $Ptcco_2$ target value of 60 mmHg, the mean duration of the apnea test (11 ± 4 *vs.* 20 ± 0 min; $P < 0.001$), hypercapnia (74.0 ± 4.9 *vs.* 98.3 ± 20.0 mmHg; $P < 0.001$), acidosis (pH: 7.18 ± 0.06 *vs.* 7.11 ± 0.08; $P < 0.001$), and decrease in arterial oxygen partial pressure (−47 ± 44 *vs.* −95 ± 89; $P < 0.05$) at the end of the test were reduced as compared with the 20-min apnea test group.**

Conclusion: **During the apnea test in brain-dead patients, a $Ptcco_2$ of 60 mmHg accurately predicts that a $Paco_2$ of 60 mmHg has been reached. This may allow a reduction in the duration of the apnea test and consecutively limit occurrence of complications.**

TC-CO_2 Monitoring & Transport

Jacob J et al, *Crit Care Med* 1986;12:1050

- TC-CO_2 monitoring during neonatal transport
  - 32 neonates with respiratory failure
  - control (no monitor) vs. monitored
- monitored patients
  - no hypercarbia on arrival vs. 2 in control group
  - more time in desired CO_2 range (35-45 mmHg), $p<0.02$

TC-CO_2 Monitoring & Transport

O'Connor TA et al, *J Perinatology* 1998;18:189

- prospective trial, infants transported more than 30 miles
- control (no monitor) vs. TC-CO2 monitoring
- monitored infants
  - PIP lowered during transport
    - -1.5 vs. +0.6 cmH_20, $p<0.04$
  - more likely to arrive with normal pH & PaCO2
    - p=0.03 & 0.01
  - no difference in initial stabilization time at referring hospital

Established in 1871

Swiss Medical Weekly

Formerly: Schweizerische Medizinische Wochenschrift

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Transcutaneous versus blood carbon dioxide monitoring during acute noninvasive ventilation in the emergency department – a retrospective analysis

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TC-CO_2 Monitoring

- advantages

tes

- accuracy affected by low perfusion states
  - use of inotropic agents with vasoconstricting properties
  - lag time in CO_2 response
  - potential for superficial blister
  - less familiarity with its use when compared to $ETCO_2$

Tobias JD. Transcutaneous carbon dioxide monitoring in infants and children. *Pediatr Anesth* 2009;19:434-444

- Transcutaneous CO_2 monitoring provides an accurate continuous estimation of arterial CO_2 in most clinical scenarios.
- End-tidal CO_2 monitoring remains the standard of care to document the intratracheal position of the endotracheal tube.
- ET-CO2 generally < PaCO2 < TC-CO2
- Consider using both monitors for critically ill patients.
- There is expanding use of TC-CO_2 monitoring outside of the PICU including postoperative monitoring of respiratory status in patients receiving opioids.

APSF believes that clinically significant drug-induced respiratory depression in the postoperative period remains a serious patient safety risk that continues to be associated with significant morbidity and mortality since it was first addressed by APSF in 2006.

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