BLOOD GASES AND TRANSCUTANEOUS MONITORING IN THE NICU AND PICU

NICU, neonatal intensive care unit; PICU, paediatric intensive care unit.

INTRODUCTION

INTRODUCTION

Welcome to this presentation on the use of blood gas and transcutaneous monitoring (TCM) in neonatal and paediatric critical care

This presentation has been developed by an international panel of experts in neonatology: Prof. Olivier Danhaive, Dr. Kaare Lundstrøm, Prof. Anton van Kaam and Prof. Daniele de Luca

Blood gas monitoring is relevant in the assessment of the patient, particularly of neonates. Healthcare professionals at the neonatal (NICU) and paediatric intensive care units (PICU) require thorough knowledge of all aspects of blood gases, TCM and the interpretation of the results, enabling them to implement the technique appropriately in clinical practice

LEARNING OBJECTIVES

LEARNING OBJECTIVES

- Upon completion of this presentation you will:
  - Understand how TCM fits in the wider picture of blood gas monitoring, and what the added value of TCM parameters is (transcutaneous partial pressure of carbon dioxide [tcpCO_2]) and oxygen [tcpO_2])
  - Know the indications for TCM in neonatal and paediatric critical care
  - Understand the practical aspects of TCM technology and know how to use the technology correctly (from a clinical user's perspective)
  - Interpret results and implement required action based on the results
- Upon completion of the e-learning, upon which this presentation is based, you can take an assessment to test your improved understanding and receive your certificate of accreditation

TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

SCIENTIFIC COMMITTEE

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Position:
- Associate Professor of Neonatology, France
- Neonatologist in Chief

Relevant experience:
- Consultant in Neonatology since 2007
- Associate Professor in Neonatology since 2012
- European Society for Paediatric and Neonatal Intensive Care (ESPNIC) General Secretary since 2016
- European Society for Paediatric Research (ESPR) Scientific Content Manager and Council member 2013 - 2017
- Author of > 130 scientific publications and book chapters
- Research on surfactant catabolism and development of new drugs and ventilatory strategies for paediatric and neonatal respiratory failure

Olivier Danhaive, MD

Position:
- Professor of Paediatrics, Belgium

Relevant experience:
- Consultant in Neonatology since 1992
- Chief of Neonatology since 2011
- Board member of the ESPR pulmonology section since 2016
- Author of > 40 scientific publications and book chapters
- Clinical and basic research in surfactant biology and human lung developmental disorders

Kaare E. Lundstrøm, MD

Position:
- Senior Consultant in Paediatrics, Denmark

Relevant experience:
- > 30 years of clinical experience in NICU, PICU and paediatric emergency medicine
- Lecturer at the University of Copenhagen
- Author of > 50 scientific publications and book chapters
- > 500 international scientific presentations
- Course director at European Paediatric Advanced Life Support courses since 2003 and former course director at international courses on life support
- Main interests: in blood gas physiology, monitoring in NICU and PICU, cerebral and systemic circulation in preterm neonates and neonatal and paediatric pharmacology

Anton van Kaam, MD, PhD

Position:
- Professor of Neonatology, The Netherlands

Relevant experience:
- Consultant in Neonatology since 1999
- Professor of Neonatology since 2014
- Chief of Neonatology since 2010
- Experimental and clinical research in the field of lung physiology, control of breathing, respiratory support, ventilator induced lung injury and lung protective ventilation in neonatology
- Involved in large national and international clinical trials

NICU, neonatal intensive care unit; PICU, paediatric intensive care unit.

CONTENT

- TCM IN THE WIDER CONTEXT OF BLOOD GAS MONITORING IN NEONATAL AND PAEDIATRIC CRITICAL CARE; THE ADDED VALUE OF TCM PARAMETERS
- INDICATIONS FOR TCM IN NEONATAL AND PAEDIATRIC CRITICAL CARE
- PRACTICAL ASPECTS OF TCM TECHNOLOGY IN NEONATOLOGY
- INTERPRETATION OF THE RESULTS OF TCM
- SUMMARY

TCM, transcutaneous monitoring.

TRANSCUTANEOUS MONITORING (TCM) IN THE WIDER CONTEXT OF BLOOD GAS MONITORING IN NEONATAL AND PAEDIATRIC CRITICAL CARE

INTRODUCTION

LEARNING OBJECTIVE

- Understand how TCM fits in the wider picture of blood gas monitoring, and what the added value of TCM parameters is (tcpO_2 and tcpCO_2)

Neonatal blood gas monitoring is important

- Although the survival of premature neonates has increased in recent years, a significant proportion of children cope with minor or major morbidity after discharge and later in life[1-3]
- Preterm neonates are vulnerable to changes in blood gas values

1. Johnson S, et al. *Early Hum Dev.* 2016;103:69-75. 2. Marlow N, et al. *N Engl J Med.* 2005;6;352:9-19. 3. Johnson S, et al. *Arch Dis Child Fetal Neonatal Ed.* 2015;100:F301-8.

TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

PRETERM NEONATES ARE VULNERABLE TO CHANGES IN BLOOD GAS VALUES

High oxygen partial pressure (pO_2)

- Oxidative damage[1] is associated with
  - Acute lung injury and bronchopulmonary dysplasia (BPD)[2]
  - Retinopathy of prematurity (ROP)[3]
  - White matter injury[1]
  - Oxygen organ toxicity[4]

High carbon dioxide partial pressure (pCO_2)

- Increased mortality[9]

Low pO_2

- Centralised blood flow to brain and heart is associated with an increased incidence of
  - Necrotising enterocolitis (NEC)[3]
  - Acute kidney failure[5]
- Pulmonary arterial hypertension (PAH)[6]
- Impaired neurological development[7]
- Increased mortality[8]

Low pCO_2

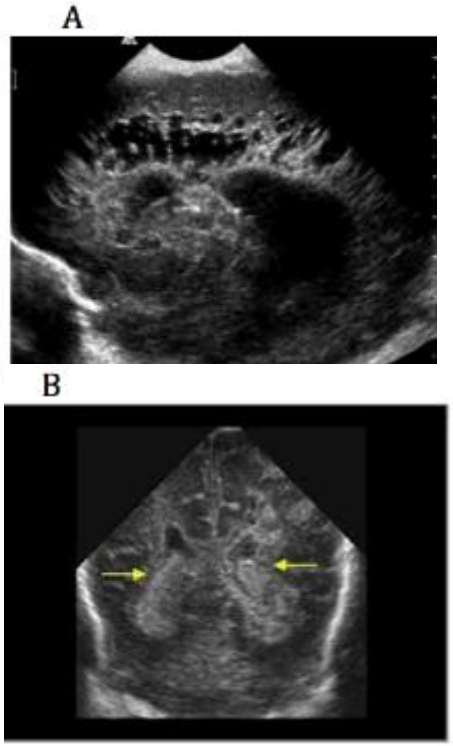
- Associated with increased incidence of BPD[2,10]
- Causes reduction in cerebral blood flow[10]
  - Increased risk of ischemia
  - Increased risk of white matter injury
  - Increased risk of adverse neurologic outcome
- Limits cerebral metabolism[10]

1. Perrone S, et al. *Front Pediatr.* 2017;4:143. 2. Northway WH. *Arch Dis Child.* 1990;65(10 Spec No):1076-81. 3. BOOST II United Kingdom, Australia, and New Zealand Collaborative Groups. *N Engl J Med.* 2013;368:2094-104. 4. Sola A, et al. *Acta Paediatr.* 2014;103:1009-18. 5. Husain-Syed F, et al. *Am J Respir Crit Care Med.* 2016;194:402-14. 6. Danhaive O, et al. *J Perinatol.* 2005;25:495-9. 7. Sweet DG, et al. *Neonatology.* 2017;111:107-25. 8. Askie LM, et al. *Cochrane Database Syst Rev.* 2017;4:CD011190. 9. Thome UH, et al. *Neonatology.* 2018;113:221-30. 10. Erickson SJ, et al. *J Paediatr Child Health.* 2002;38:560-2.

THE IMPORTANCE OF BLOOD GAS MONITORING: THE ROLE OF CO_2 AND O_2 IN THE CEREBRAL CIRCULATION

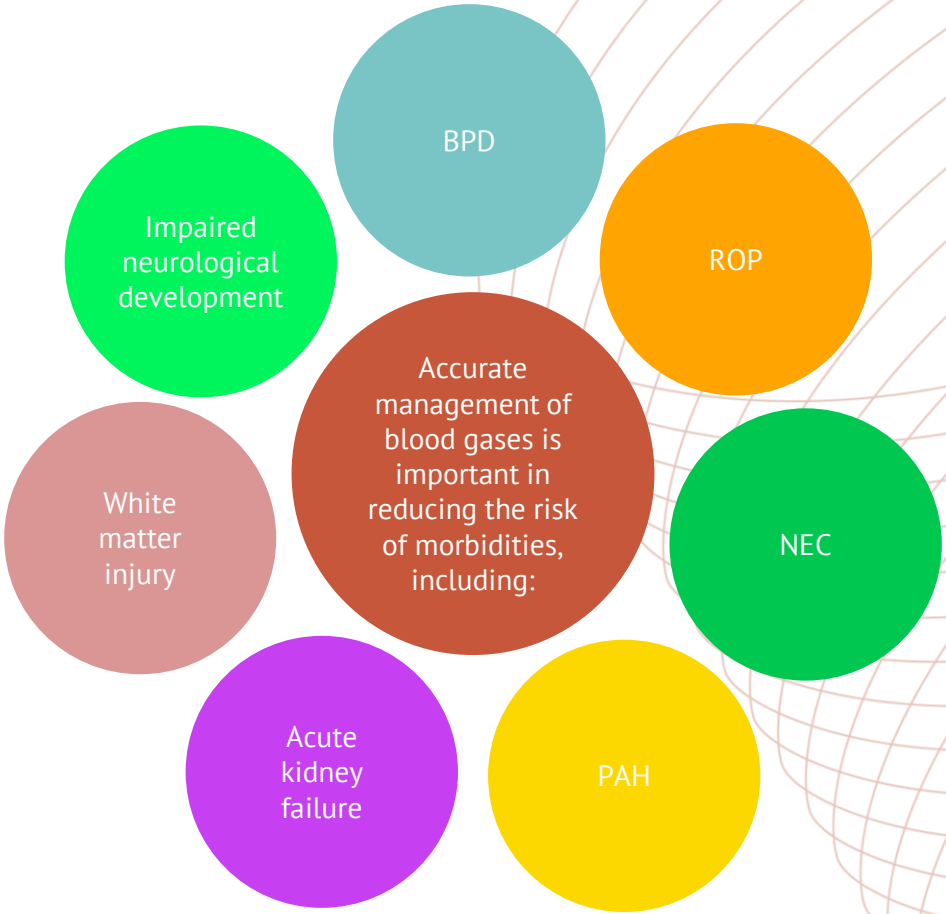
	CO_2 acts as a cerebral vasodilator	**O_2 acts as a cerebral vasoconstrictor**
High	High pCO_2 values lead to **increased** cerebral blood flow	High pO_2 values lead to **reduced** cerebral blood flow
Low	Low pCO_2 values lead to **reduced** cerebral blood flow	Low pO_2 leads to **increased** cerebral blood flow

- **Low *p*CO_2** (hyperventilation) or **high *p*O_2** (uncontrolled hyperoxemia) levels increase the risk for preterm infants of ischemic lesions, such as periventricular leukomalacia (A) or white matter injury
- Similarly, **low *p*O_2** (respiratory failure, insufficient ventilatory support) may predispose to cerebral haemorrhage (B)
  - No association between high *p*CO_2 and brain damage has been demonstrated
- **This stresses the importance of close monitoring of blood gases in preterm infants**



1. Pryds O, et al. *Acta Paediatr Scand Suppl.* 1989;360:33-6. 2. Graziani LJ, et al. *Pediatrics.* 1992;90:515-22.
CO_2, carbon dioxide; O_2, oxygen; *p*CO_2, carbon dioxide partial pressure; *p*O_2, oxygen partial pressure.

ACCURATE MANAGEMENT OF BLOOD GASES IS IMPORTANT IN REDUCING THE RISK OF MORBIDITIES



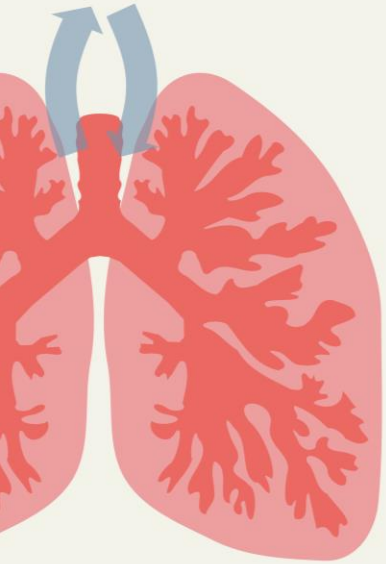
BPD, bronchopulmonary dysplasia; NEC, necrotising enterocolitis; PAH, pulmonary arterial hypertension; ROP, retinopathy of prematurity.

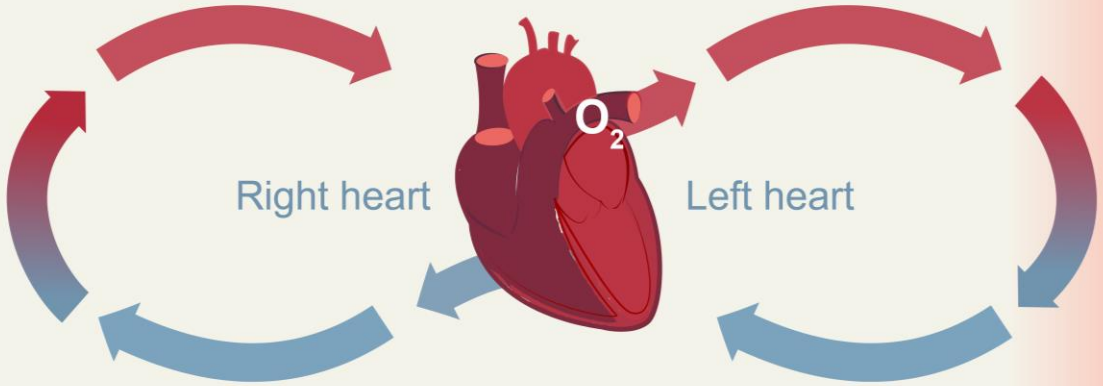
BLOOD GASES CAN BE MONITORED IN THE AIRWAYS, OR IN ARTERIAL OR CAPILLARY BLOOD

Airways	Arterial blood	Capillary blood









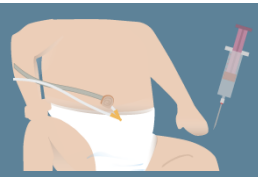
- End-tidal monitoring of pCO_2

- Blood gas analysis of pO_2 and pCO_2 in arterial blood
- Pulse oximetry to monitor O_2 saturation

- Blood gas analysis of pO_2 and pCO_2 in capillary blood
- TCM of pO_2 and pCO_2

O_2, oxygen; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure.

BLOOD GASES CAN BE MONITORED INTERMITTENTLY OR CONTINUOUSLY



Blood gas analysis

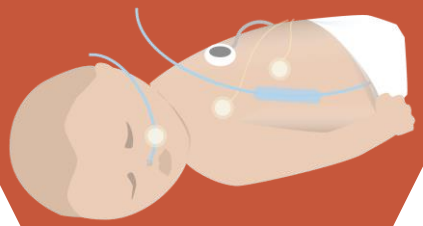
- Blood for analysis of pO_2 and pCO_2 in arterial blood can be obtained via arterial puncture or an arterial catheter
- Blood for analysis of partial pressure of pO_2 and pCO_2 in capillary blood can be obtained by a heel stick

Pulse oximetry

- Most commonly used method for monitoring oxygenation
- Non-invasive
- No accurate detection of hyperoxemia
- No CO_2 monitoring

TCM

- Continuous, non-invasive monitoring of tc*p*O2 and tcpCO_2



End-tidal CO_2 monitoring

- Measures CO_2 in the exhaled air, at the relatively flat portion of the expiratory phase
- Suitable for use in larger children (≥ 2 kg) without lung disease, in specific situations, such as elective surgery, transport or hypothermia
- Not suitable for use in extremely premature children, as it adds dead space
- Poor correlation between end-tidal and arterial pCO_2 levels[1]

Near-infrared spectroscopy (NIRS)

- Measures cerebral oxygen saturation

End-tidal CO_2 monitoring

Intermittent: blue
Continuous: orange

1. Tobias JD, et al. *Anesth Analg.* 1997;85:55-8.

CO_2, carbon dioxide; O_2, oxygen; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen

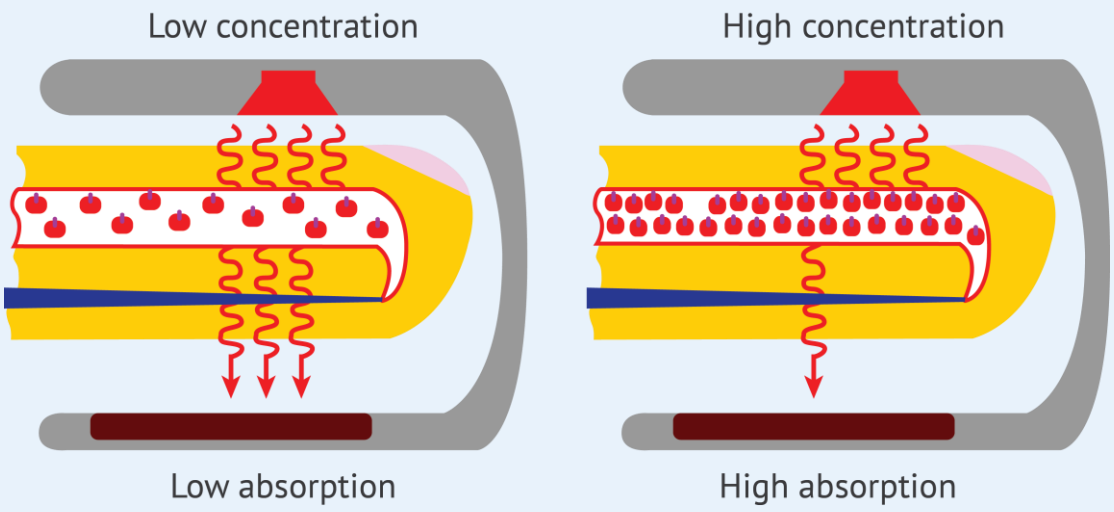
PULSE OXIMETRY MONITORS OXYGENATION

Pulse oximetry monitors oxygenation

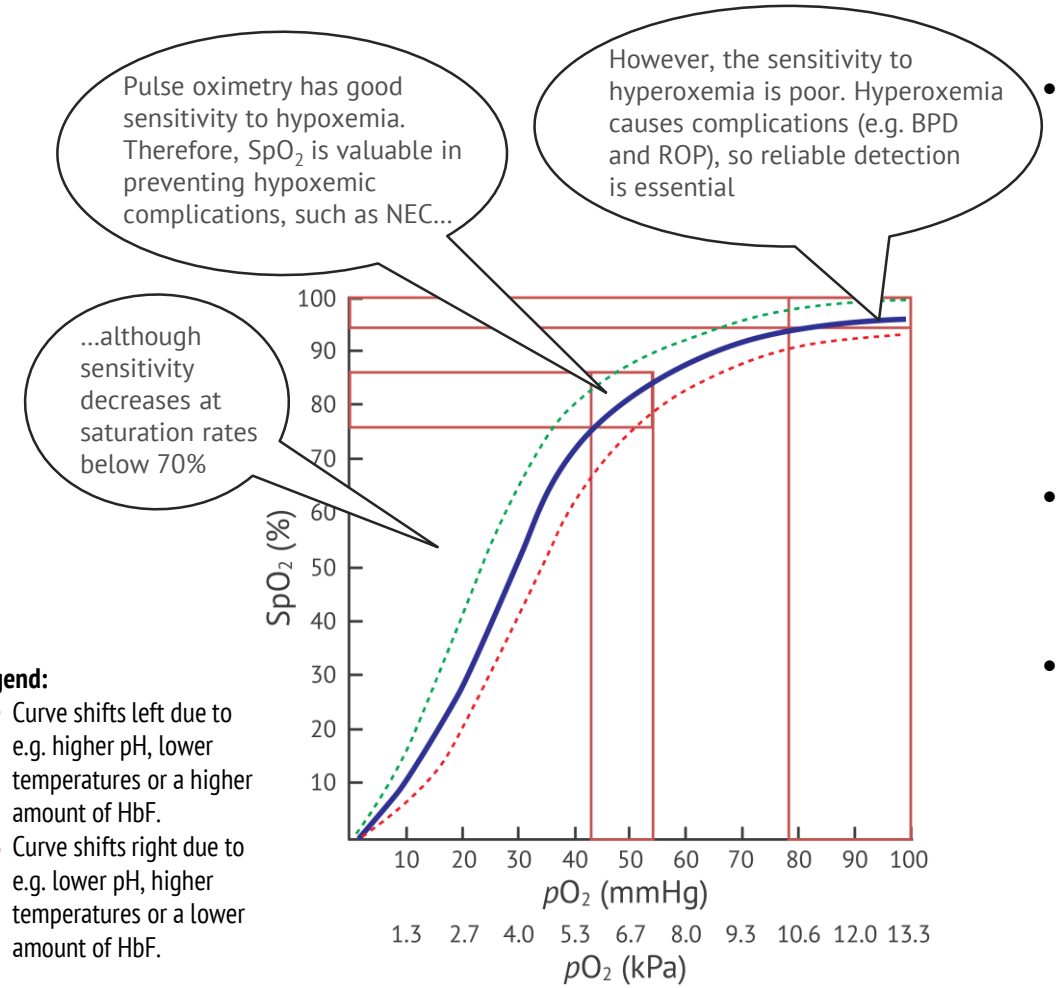
- The device measures the light absorption of oxyhaemoglobin (HbO_2) and deoxyhaemoglobin
- Oxygen saturation (SpO_2) is reported as a percentage
  - HbO_2 / (HbO_2 + deoxyhaemoglobin)

Pulse oximetry is non-invasive and easy to use

HOW PULSE OXIMETRY WORKS



PULSE OXIMETRY ALONE CANNOT BE USED TO PREVENT COMPLICATIONS OF HYPEROXEMIA

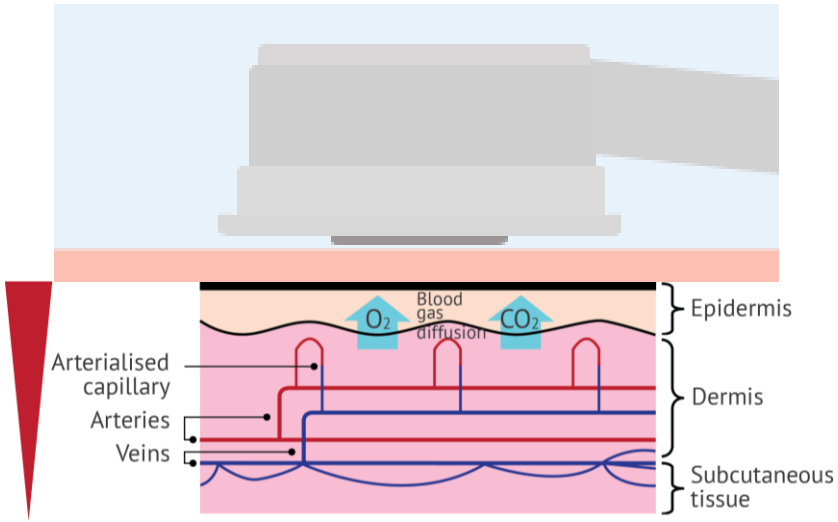


- The oxygen dissociation curve shows the relationship between pO_2 and SpO_2 measured by pulse oximetry
  - This relationship is affected by many factors, including pH, temperature, percentage of foetal Hb (HbF), and blood transfusions
- In premature neonates, the percentage of HbF is variable and unpredictable[1,2]
- SpO_2 cannot be used reliably to determine oxygenation becaus e of the wide variation of partial pressure of oxygen values associated with oxygen saturation values > 95%

1. Colombo B, et al. *Br J Haematol.* 1976;32(1):79-87. 2. De Luca D, et al. *Lancet Respir Med.* 2017;5:657-66.
BPD, bronchopulmonary dysplasia; NEC, necrotising enterocolitis; pO_2, oxygen partial pressure; ROP, retinopathy of prematurity; SpO_2, oxygen saturation.

TRANSCUTANEOUS DEVICES MEASURE CUTANEOUS LEVELS OF OXYGEN AND CARBON DIOXIDE

- TCM devices use the capillary blood for monitoring
- TCM measures blood gas levels through the skin
  - Therefore, TCM devices can monitor both O_2 and CO_2
- The sensor is placed on the skin, where a heating element elevates the skin temperature, causing dilatation of the underlying capillaries and increasing the gas diffusion through the skin
- CO_2 and O_2 diffuse through the skin to the sensor

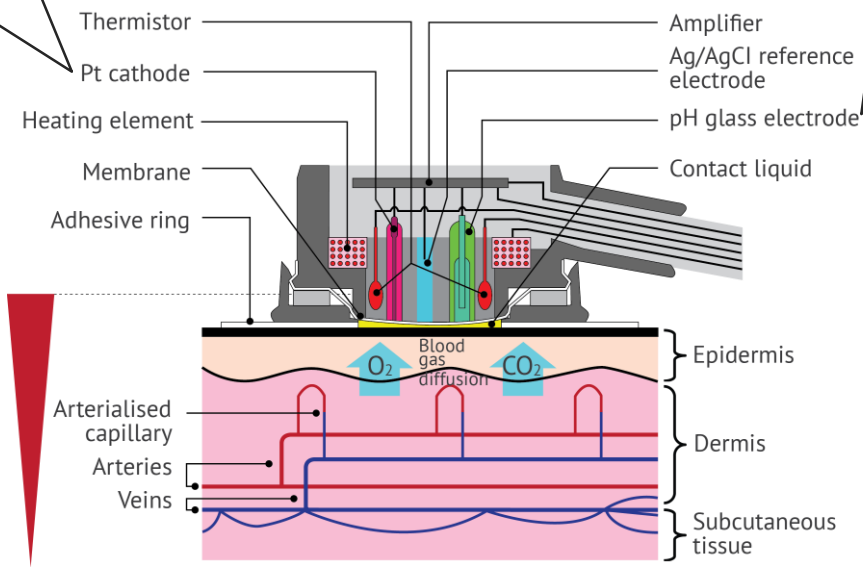


CO_2, carbon dioxide; O_2, oxygen; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring.

TECHNOLOGY PRINCIPLE OF TCM

Clark principle for O_2
O_2 diffuses through the skin and the membrane to the cathode. After conversion, the sensor algorithm generates a tcpO_2 in mmHg or kPa.

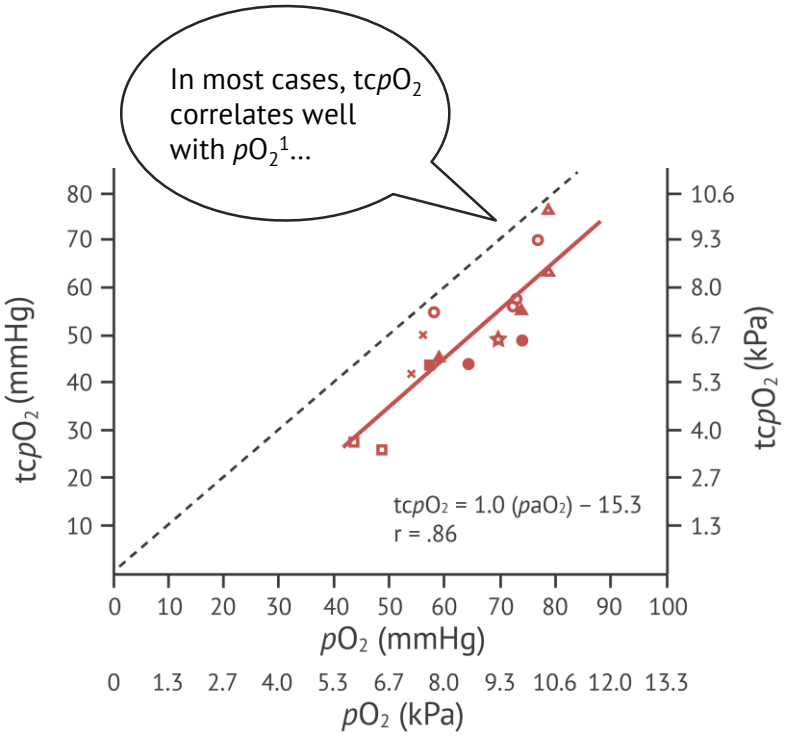
Stow-Severinghaus principle for CO_2
CO_2 reacts with water forms carbonic acid and dissociates into H+ which are interpreted through a pH glass element. After conversion, the sensor algorithm generates a tcpCO_2 in mmHg or kPa.

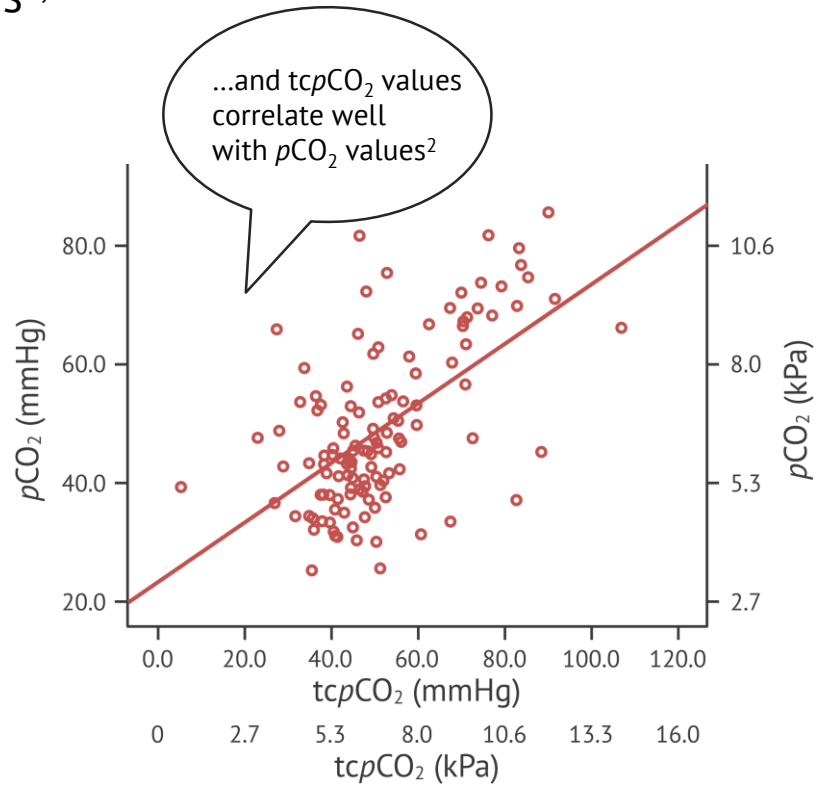


Ag/AgCl, silver chloride electrode; CO_2, carbon dioxide; O_2, oxygen; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous carbon dioxide pressure; tcpO_2, transcutaneous oxygen pressure.

tcpO_2/tcpCO_2 AND pO_2/pCO_2 ARE STRONGLY RELATED, BUT TELL A DIFFERENT STORY

- TCM measures pO_2 and pCO_2 diffused through the skin, not in arterial blood
- In haemodynamically stable patients, there is good correlation between transcutaneous (TC) and arterial values[1,2]

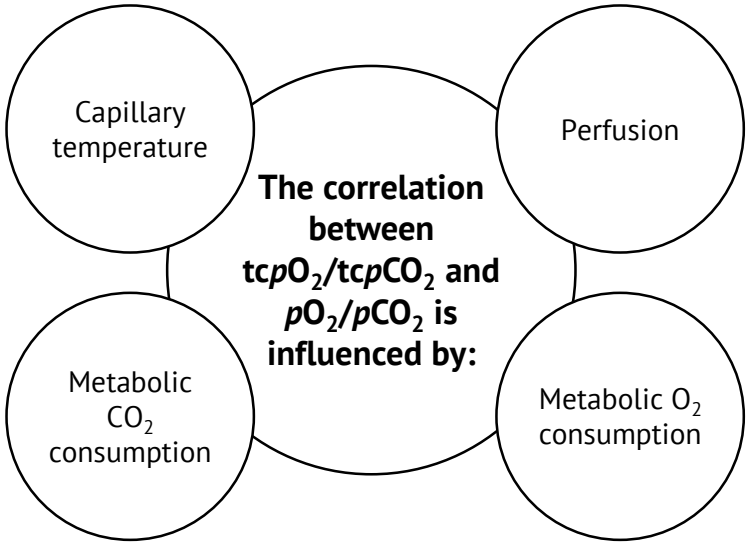




1. Used with permission from: Rome ES, et al. *Pediatrics*. 1984;74:217-20. 2. Used with permission from: Aly S, et al. *Am J Perinatol*. 2017;34:480-5.
pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide ; tcpO_2, transcutaneous partial pressure of oxygen..

tcpO_2/tcpCO_2 AND pO_2/pCO_2 ARE STRONGLY RELATED, BUT TELL A DIFFERENT STORY

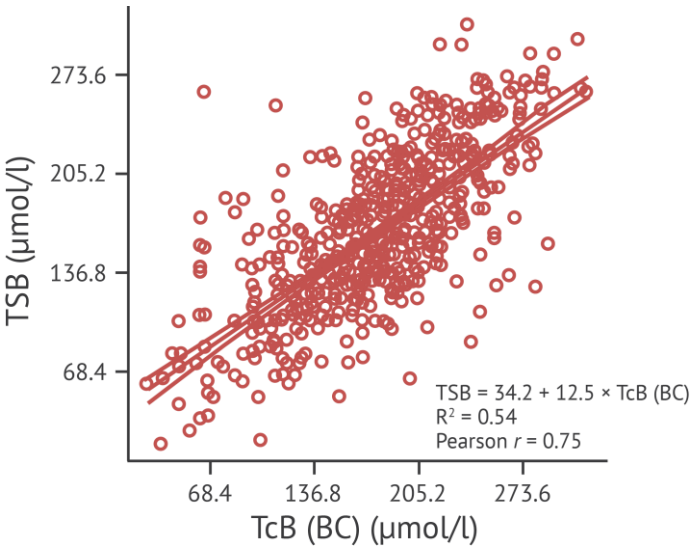
- However, tcpO_2 and tcpCO_2 are influenced by perfusion and metabolism
  - Therefore, the correlation between tcpO_2/tcpCO_2 and pO_2/pCO_2 can be variable, for example in the case of a haemodynamic problem
- **TCM is valuable for trend analysis of pO_2 and pCO_2**

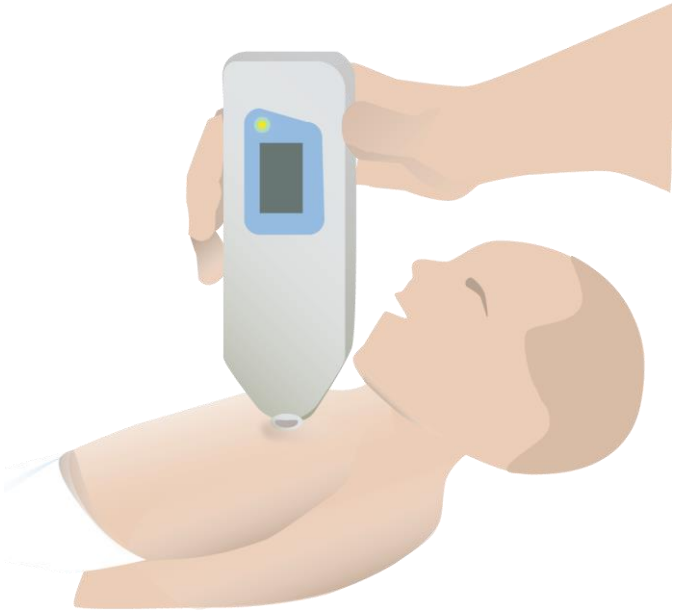


CO_2, carbon dioxide; O_2, oxygen; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide ; tcpO_2, transcutaneous partial pressure of oxygen.

TCM SHOWS A TREND, SIMILAR TO TC BILIRUBINOMETRY

- TC bilirubinometry (TCb) is widely used for monitoring a trend in bilirubin values
- Values from TCb are different from the total serum bilirubin values and require initial calibration with laboratory measurements
  - TCM shows a trend, similar to TCb to monitor bilirubin values





Used with persmission from: De Luca D, et al. *Arch Dis Child Fetal Neonatal Ed.* 2008;93:F135-9.
TC, transcutaneous; TCb, transcutaneous bilirubinometry; TCM, transcutaneous monitoring.

TCM OFFERS ADDED VALUE OVER PULSE OXIMETRY, BLOOD GAS ANALYSIS AND END-TIDAL MONITORING

	tcpO_2 tcpCO_2	SpO_2	pO_2 pCO_2	$EtCO_2$
Monitoring oxygen and carbon dioxide	+	Oxygenation only	+	Carbon dioxide only
Continuous measurement	+	+	-	+
Accuracy in motion artefacts	+	-	+	+
Stable performance with arrhythmias	+	-	+	?
Invasive method	-	-	+	-
Accurate with low pO_2 (SpO_2 < 70%)	+	-	+	-
Detection of hyperoxemia	+	+/-	+	-
Detection of hypoventilation	+	-	+	+
Detection of hyperventilation	+	-	+	+
Added dead space	-	-	-	+

TCM rapidly detects hyper/ hypoxemia and hyper/ hypocapnia, preventing serious adverse outcomes

TCM may help reduce the need for blood gas analysis[1], reducing:
- Risk of complications
- Stress and pain
- Blood loss leading to low Hb, potentially requiring blood transfusion

TCM allows for continuous detection of hyperoxemia, preventing oxygen toxicity (e.g. BPD, ROP)

End-tidal monitoring complicates ventilation in neonates, due to the addition of dead volume

1. Mukhopadhyay S, et al. *Respir Care*. 2016;61:90-7.

BPD, bronchopulmonary dysplasia; $EtCO_2$, partial pressure of end-tidal carbon dioxide; Hb, haemoglobin; pO_2, oxygen partial pressure; ROP, retinopathy of prematurity; SpO_2, oxygen saturation; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

SUMMARY

Preterm neonates are very vulnerable to changes in blood gases

- Accurate management of blood gases is important in reducing the risk of morbidity

pO_2 and pCO_2 can be intermittently or continuously monitored in the airways or in arterial or capillary blood

- Blood gas analysis is the gold standard, but requires an invasive procedure and does not allow for continuous monitoring
  - Taking repetitive samples is disadvantageous for the blood volume of the neonate
- Pulse oximetry monitors oxygenation, is non-invasive and easy to use
  - However, it does not accurately detect hyperoxemia and cannot be used to monitor pCO_2
- End-tidal CO_2 monitoring adds dead space and cannot be used to monitor pO_2, but can be valuable in specific situations, such as elective surgery in larger children
  - However, there is a poor correlation between end-tidal and arterial pCO_2 levels

1. Mukhopadhyay S, et al. *Respir Care*. 2016;61:90-7.

CO_2, carbon dioxide; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring.

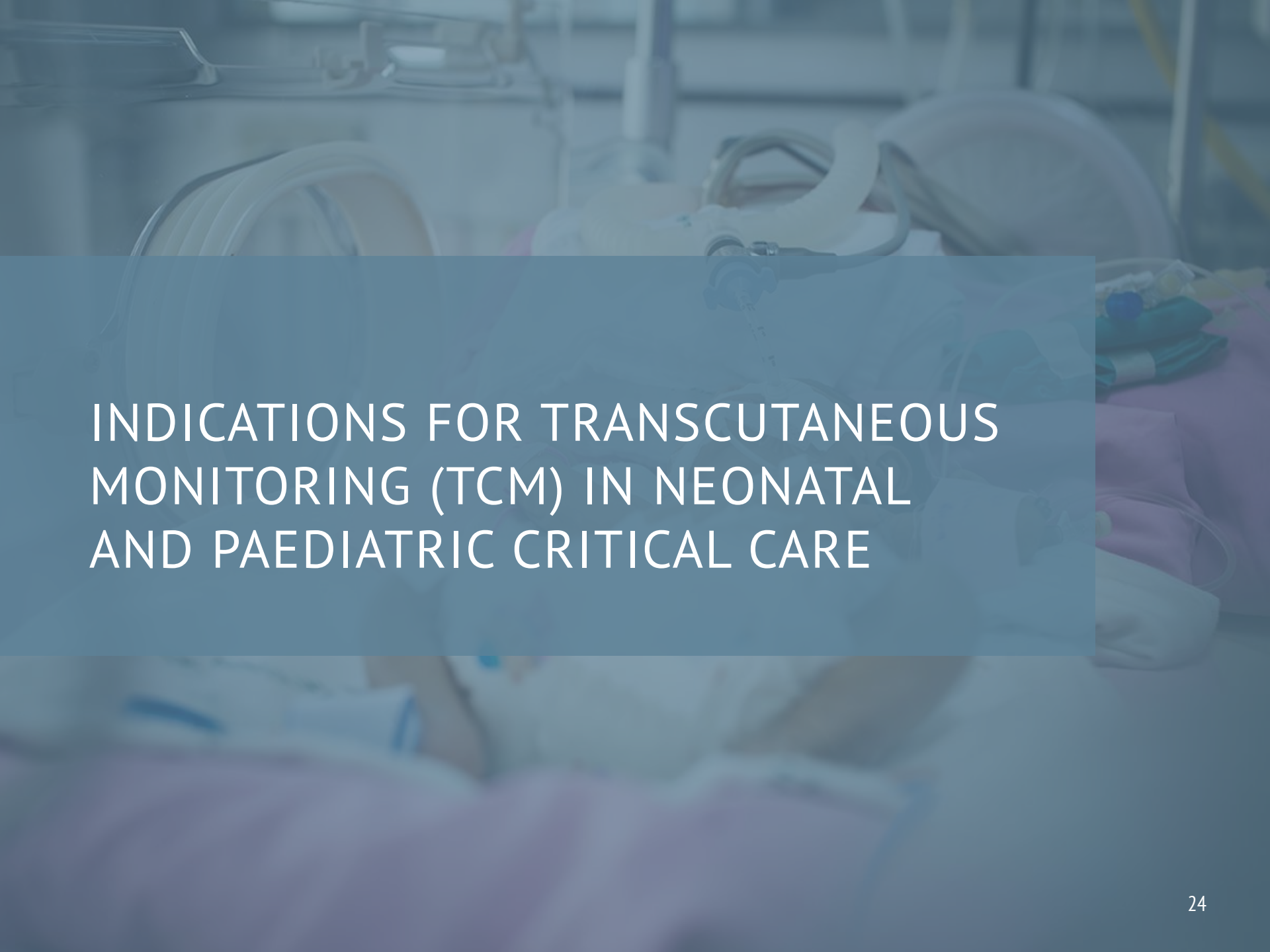
SUMMARY (continued)

TCM adds value by allowing for continuous monitoring and rapid detection of both hyper/hypoxemia and hyper/hypocapnia

- TCM allows for continuous monitoring of both pO_2 and pCO_2
- TCM allows for detecting hyperoxemia, which is important in preventing oxygen toxicity
- TCM may help reduce the need for invasive blood gas measurement[1], lowering the risk of infections, stress, pain and low Hb levels potentially requiring blood transfusions
- TCM can be an important piece of the monitoring puzzle, providing valuable information when assessing and monitoring critically ill children

1. Mukhopadhyay S, et al. *Respir Care*. 2016;61:90-7.

Hb, haemoglobin; pCO_2, carbon dioxide partial pressure; pO_2, oxygen partial pressure; TCM, transcutaneous monitoring.



INDICATIONS FOR TRANSCUTANEOUS MONITORING (TCM) IN NEONATAL AND PAEDIATRIC CRITICAL CARE

INTRODUCTION

LEARNING OBJECTIVE

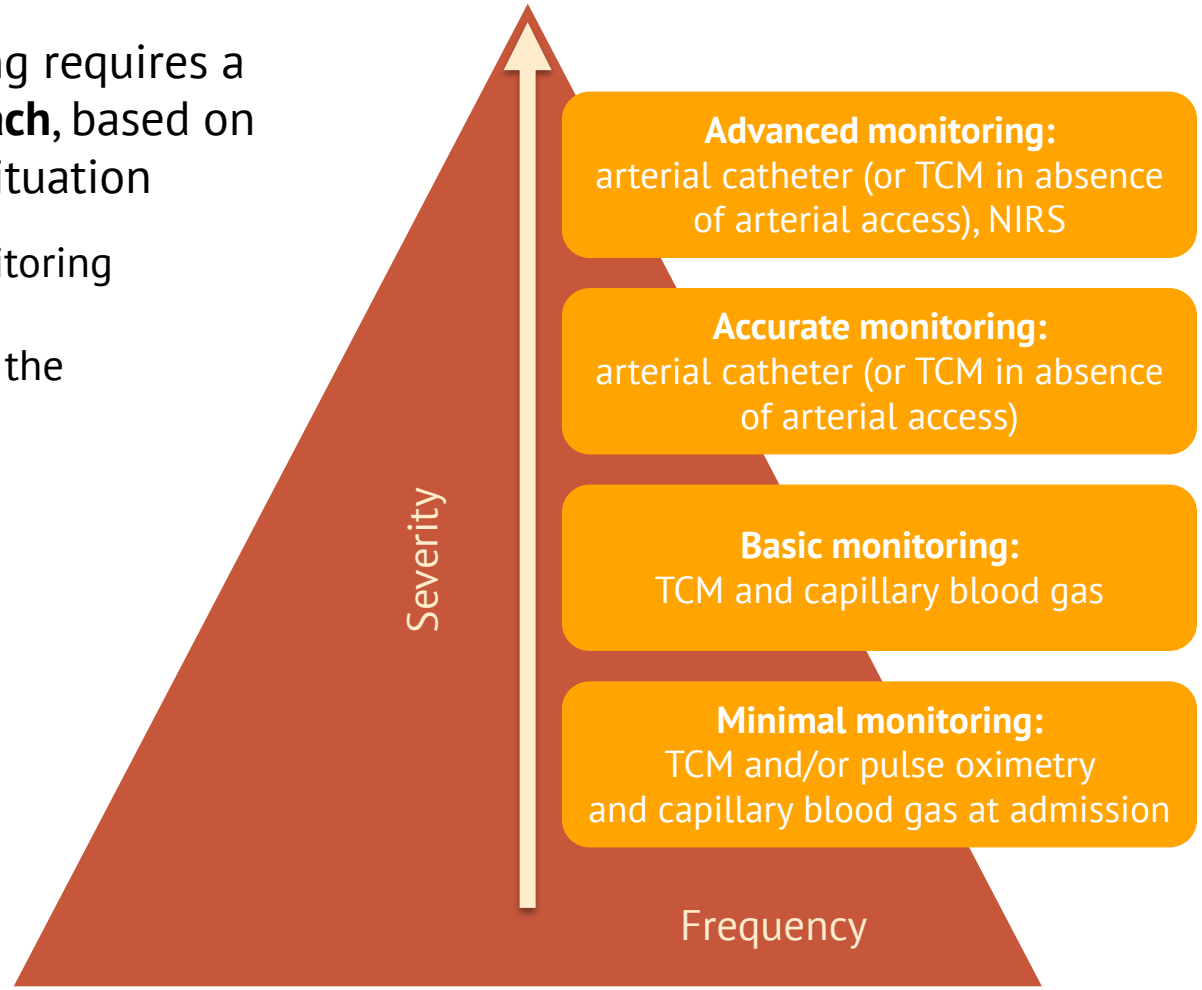
- Know the indications for TCM in neonatal and paediatric critical care

Indications are those situations in which TCM is valuable for blood gas monitoring in the NICU and PICU

NICU, neonatal intensive-care unit; PICU, paediatric intensive-care unit; TCM, transcutaneous monitoring.

MODALITIES FOR BLOOD GAS MONITORING, DEPENDING ON THE SEVERITY OF THE SITUATION

- Blood gas monitoring requires a **personalised approach**, based on the severity of the situation
  - The different monitoring techniques are complementary to the clinical picture



Modified with permission from: De Luca D, et al. *J Pédiatrie Puériculture*. 2015;28:276-300.
NIRS, near-infrared spectroscopy; TCM, transcutaneous monitoring.

TCM IS A VALUABLE PART OF A PERSONALISED MONITORING APPROACH IN UNSTABLE CHILDREN AND CHILDREN REQUIRING RESPIRATORY SUPPORT

- TCM is valuable in unstable children and children with rapidly changing blood gases
- In the PICU, TCM is especially valuable in infants (⩽ 2 years old), as their skin is still relatively thin
  - E.g. infants with respiratory syncytial virus (RSV) infections

tc*p*O_2 provides information on **oxygenation**

- In children on **mechanical ventilation**, tc*p*O_2 is useful for managing ventilatory pressures and lung volume, escalating and weaning
- tc*p*O_2 measurement can also be useful during the **acute phase of hypoxemia**, like in respiratory distress syndrome (RDS), neonatal acute respiratory distress syndrome (ARDS), and persistent pulmonary hypertension of the newborn (PPHN)
- tc*p*O_2 monitoring can be useful to prevent hyperoxemia during **procedures**, such as **surfactant** administration or pneumothorax drainage

tc*p*CO_2 provides information on **ventilation**

- In children on **mechanical ventilation**, tc*p*CO_2 is useful for managing ventilation settings, escalating and weaning
  - Especially in children on high frequency ventilation (**HFV**), as they have a high risk of hypocapnia
- tc*p*CO_2 can also be useful in **spontaneously breathing children**, e.g. during transport, following procedures or in patients who are otherwise **unstable**
- tc*p*CO_2 measurement can be valuable during administration of **surfactant**, as surfactant may cause transient hypercapnia

PICU, paediatric intensive care unit; TCM, transcutaneous monitoring; tc*p*CO_2, transcutaneous partial pressure of carbon dioxide; tc*p*O_2, transcutaneous partial pressure of oxygen.

SUMMARY

Blood gas monitoring requires a personalised approach, based on the severity of the situation

- Technology is complementary to the clinical picture
- It is important to be aware of the limitations of each monitoring modality

TCM is valuable in unstable children and children with rapidly changing blood gases

- tcpO_2 provides information on oxygenation
- tcpCO_2 provides information on ventilation

TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

PRACTICAL ASPECTS OF TRANSCUTANEOUS MONITORING (TCM) TECHNOLOGY IN NEONATOLOGY

INTRODUCTION

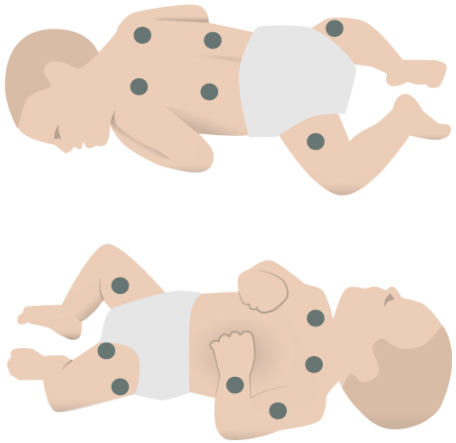
LEARNING OBJECTIVE

- Understand the practical aspects of TCM technology and know how to use the technology correctly

This section focuses on the clinical user's perspective

TCM, transcutaneous monitoring.

PRACTICAL ASPECTS OF MEASURING SITES AND PLACING THE SENSOR



- The ideal measuring site for TCM is an area of skin over a homogeneous capillary bed, with no large veins or skin defects
  - All central areas, except for the head, can be suitable
  - The sensor should not be placed directly on top of a bone or scar or at a location with severe oedema, as this may affect the results
  - It is important the baby does not lie on the sensor, to prevent decubitus
- The sensor must be in full contact with the skin, using contact liquid or gel together with the fixation ring
  - Air bubbles result in overestimating tcpO_2 and underestimating tcpCO_2 levels
- After placing the sensor, a stabilisation time needs to be taken into account; during this time, the sensor slowly warms up the skin
  - Around 5 minutes for tc$pCO2$ and around 10 minutes for tcpO_2 values
- It is important to frequently move the sensor
  - This can be done by placing 2 or 3 fixation rings and changing sensor position between these rings
  - The recommended frequency depends on the temperature of the sensor
- The sensor should periodically be recalibrated

TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

SENSOR TEMPERATURES HAVE SPECIFIC INDICATIONS AND PRACTICAL CONSIDERATIONS

Temperature skin surface / sensor core		40 / 41°C	42 / 43°C	43 / 44°C
Patient group		• Extremely low birth weight neonates • Extremely immature neonates	• Low birth weight neonates • Preterm neonates	• Preterm neonates • Term neonates • PICU patients
Max. time at one location		• 4-6 hours	• 3 hours	• 15-20 minutes in preterm neonates • 3-4 hours in term neonates and PICU patients
Correlation	tcpCO_2	• Long-term trend observation	• Short-term trend observation	• Short-term observation and snapshot monitoring • Helps estimate pCO_2
	tcpO_2	• Generally poor correlation, as the capillary bed will not be sufficiently arterialised • May provide a long-term trend outlook in extremely immature neonates, as their skin is very thin	• Short-term trend observation in preterm neonates • Long-term trend monitoring • Detection of hyper/hypoxemia	• Short-term observation and snapshot monitoring • Predicts pO_2 • Can be used for calculating oxygenation index
Limitations		• Low temperature limits accuracy for tcpO_2 • Longer stabilisation time for tcpCO_2	• In patients with vulnerable skin, the sensor site may need to be changed in shorter intervals	• In preterm neonates, the maximum time at one location is short, so only useful for intermittent monitoring

pCO_2, carbon dioxide partial pressure; PICU, paediatric intensive care unit; pO_2, oxygen partial pressure; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

POTENTIAL ADVERSE EFFECTS OF TCM CAN BE AVOIDED

SKIN BURNS

- A premature baby has a thin, immature and sensitive skin. Therefore, it is important to check the temperature of the sensor and the time the sensor has been applied to the body
- Modern TCM monitors keep track of this information
  - A Danish study in 40 premature and term neonates, observed no skin lesions (apart from mild transient erythema) at electrode temperatures ranging from 39-44°C[1]
- Note that red spots are usually not skin burns, but red rash due to the vasodilation induced by the warmth of the sensor

SKIN IRRITATION FROM ADHESIVE RINGS

- Relocate the ring(s) every 12-24 hours

SKIN NECROSIS AND PRESSURE INJURIES

- Avoid direct pressure on the sensor
- The child should not lie on the sensor or adhesive rings

1. Sørensen LC, et al. *Scand J Clin Lab Invest.* 2011 Nov; 71(7):548-52.

TCM, transcutaneous monitoring.

SUMMARY

Measuring sites should be selected with the positioning of the neonate in mind

- The sensor must be in full contact with the skin
- Initiation of TCM involves calibration and sensor stabilisation time

Sensor temperatures have specific indications and practical considerations

- The optimal sensor temperature for reliable measurement of tcpO_2 and tcpCO_2 is ⩾ 43°C
- However, lower sensor temperatures can still produce useful trend information

Potential adverse effects of TCM can be avoided

- Keep track of the sensor temperature
- Regularly move the sensor and adhesive rings
- Make sure the child does not lie on the sensor or adhesive rings

TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

INTERPRETATION OF THE RESULTS OF TRANSUTANEOUS MONITORING (TCM)

INTRODUCTION

LEARNING OBJECTIVE

- Be able to interpret results and implement required action based on the results

This section provides a call to action, using interactive clinical case studies

TCM, transcutaneous monitoring.

CASE 1: LIZZY

Admission | Initial monitoring | Subsequent monitoring

This case study concerns Lizzy.

CASE 1: LIZZY

- Admission
  - Lizzy, 6 months old, is admitted to the PICU with RSV bronchiolitis
  - Lizzy was born at a gestational age of 28 weeks and 3 days and has a history of mild BPD
  - After admission, Lizzy deteriorates fast; she needs intubation and mechanical ventilation
  - She is monitored with electrocardiography, pulse oximetry, TCM of pO_2 and pCO_2 and continuous arterial blood pressure measurement through a peripheral arterial line

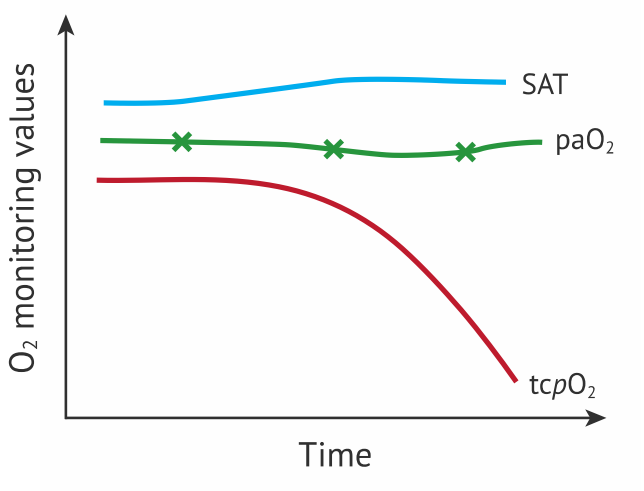
- Initial monitoring
  - After intubation, Lizzy initially has stable, acceptable values:
    - Heart rate 110-120/min
    - Blood pressure around 90/60 mmHg
    - SpO_2 94-96%
    - tcpO_2 60-67.5 mmHg (8-9 kPa)
    - tcpCO_2 45-48.75 mmHg (6-6.5 kPa)

- Subsequent monitoring
  - After a while, tcpO_2 gradually decreases to 41.25 mmHg (5.5 kPa), while the other parameters remain stable
    - The fraction of inspired oxygen (FiO_2) is increased, but this has only a minor effect on tcpO_2
    - Arterial blood gas measurement shows only a slight decrease in pO_2 (from 66 to 61.5 mmHg [8.8 to 8.2 kPa])
    - Clinically, the girl is slightly more pale and the capillary response time is prolonged to 3-4 seconds

BPD, bronchopulmonary dysplasia; FiO_2, fraction of inspired oxygen; pCO_2, carbon dioxide partial pressure; PICU, paediatric intensive care unit; pO_2, oxygen partial pressure; RSV, respiratory syncytial virus; SpO_2, oxygen saturation; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

CASE 1: LIZZY

- **tcpO_2 is not decreasing because of undetected respiratory failure or a technical problem, but due to a circulatory problem**
  - Circulatory problems cause a decrease in tcpO_2



This example illustrates how tcpO_2 values are influenced by both the respiratory and circulatory status. Here, tcpO_2 was the first parameter to alert the clinician about deterioration of the patient. Together with the other parameters and clinical examination, tcpO_2 guided us to the correct and timely treatment.

- A bolus of saline (20 ml/kg) is administered and tcpO_2 normalises

tcpO_2, transcutaneous partial pressure of oxygen.

CASE 2: JOE AND MIKE

Admission | Initial monitoring | Subsequent monitoring

This case study concerns Joe and Mike.

CASE 2: JOE AND MIKE

- Admission
  - Twin brothers Joe and Mike are born at a gestational age of 28 weeks and admitted to the NICU with severe RDS and a possible intrauterine infection
  - Both are intubated in the delivery room and started on invasive conventional mechanical ventilation. Two doses of exogenous surfactant have limited result

- Initial monitoring
  - Joe has no TCM and blood gas analysis every 6 hours (more frequent if indicated)
  - Mike does have TCM and blood gas analysis every 12 hours (more frequent if indicated)

- Subsequent monitoring
  - Joe and Mike are now three days old and are ventilated with the following settings:
    - Peak inspiratory pressure (PIP) 20 cmH_2O
    - Positive end expiratory pressure (PEEP) 6 cmH_2O
    - Rate 60/min
    - Inspiration time 0.35 sec
    - FiO_2 35%

FiO_2, fraction of inspired oxygen; NICU, neonatal intensive care unit; PEEP, positive end expiratory pressure; PIP, peak inspiratory pressure; RDS, respiratory distress syndrome; TCM, transcutaneous monitoring

CASE 2: JOE AND MIKE

Time	Joe (no TCM, blood gas analysis every 6 hours)	Mike (TCM, blood gas analysis every 12 hours)
8 am	SpO_2 slowly decreases. FiO_2 increased to 45%. Slightly more distress.	SpO_2 slowly decreases. FiO_2 increased to 45%. Slightly more distress. **tcpO_2 also shows clear deterioration of oxygenation**
9 am		**In addition to deteriorating oxygenation, there is a clear trend to increasing tcpCO2 > 52.5 mmHg (7 kPa).** Therefore, blood gas analysis is performed: pH 7.18, pCO_2 63.75 mmHg (8.5 kPa), base excess (BE) -8.5 mmol/L. PIP is increased to 24 cmH_2O.
10 am		**Increased PIP only results in modest changes in tcpCO_2.** Blood gas analysis to assess the effect of increase in PIP: pH 7.21, pCO_2 60.75 mmHg (8.1 kPa), BE -8.3 mmol/L. Hypercapnia on day 3 leads to a suspicion of a patent ductus arteriosus (PDA), which is confirmed by ultrasound.
11 am		Start treatment PDA and switch to rescue HFV because of hypercapnia
2 pm	Routine blood gas analysis shows pH 7.18, pCO_2 63.75 mmHg (8.5 kPa), base excess (BE) -8.5 mmol/L. PIP is increased to 24 cmH_2O.	
4 pm	Blood gas analysis to assess the effect of increase in PIP: pH 7.21, pCO_2 60.75 mmHg (8.1 kPa), BE -8.3 mmol/L. Hypercapnia on day 3 leads to a suspicion of patent ductus arteriosus (PDA), which is confirmed by ultrasound.	
6 pm	Start treatment PDA and switch to rescue HFV because of hypercapnia	

This case shows that TCM can result in rapid diagnosis of hypercapnia, earlier diagnosis of PDA, less blood gas sampling and earlier start of adequate treatment.

BE, base excess; FiO_2, fraction of inspired oxygen; HFV, high frequency ventilation; pCO_2, carbon dioxide partial pressure; PDA, patent ductus arteriosus; PIP, peak inspiratory pressure; SpO_2, oxygen saturation; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

CASE 2: JOE AND MIKE

- Joe and Mike are both set up on HFV, with the following initial settings:
  - MAP 15 cmH_2O
  - Delta pressure 27 cmH_2O, as this shows clear chest vibrations
  - Frequency 10 Hz
  - FiO_2 50%

FiO_2, fraction of inspired oxygen; HFV, high frequency ventilation; MAP, mean airway pressure

Interpretation of the results of TCM

CASE 2: JOE AND MIKE

Time	Joe (no TCM, blood gas analysis every 6 hours)	Mike (TCM, blood gas analysis every 12 hours)
11 am		Started on HFV. SpO_2 adequate. Good vibrations of the chest. **tcpCO_2 < 30 mmHg (4 kPa)** → delta pressure reduced to 25 cmH_2O.
11.30 am		**tcpCO_2 30 mmHg (4 kPa)** → delta pressure reduced to 22 cmH_2O.
12 am		**tcpCO_2 37.5 mmHg (5 kPa)** → blood gas analysis to verify adequate pCO_2 shows: pH 7.35, pCO_2 39 mmHg (5.2 kPa), BE -5.7 mmol/L. Acceptable blood gas. No further changes.
6 pm	Started on HFV. SpO_2 adequate. Good vibrations of the chest.	
8 pm	Blood gas analysis shows pH 7.50, pCO_2 24 mmHg (3.2 kPa), BE -5.5 mmol/L. Hypocapnia → delta pressure reduced to 25 cmH_2O.	
10 pm	Blood gas analysis to assess effect of decrease in delta pressure shows: pH 7.46, PaCO2 29.25 mmHg (3.9 kPa), BE -5.1 mmol/L. Still hypocapnia → delta pressure reduced to 22 cmH_2O.	
12 pm	Blood gas analysis to assess effect of decrease in delta pressure shows: pH 7.35, pCO_2 39 mmHg (5.2 kPa), BE -5.7 mmol/L. Acceptable blood gas. No further changes.	

This case shows that TCM can rapidly detect hyperventilation, resulting in severe and harmful hypocapnia, based on tcpCO_2-guided adjustment of delta pressure. Time in hypocapnia and thus risk of brain injury was significantly reduced, while sampling only once for blood gas analyses.

BE, base excess; FiO_2, fraction of inspired oxygen; HFV, high frequency ventilation; MAP, mean airway pressure; pCO_2, carbon dioxide partial pressure; SpO_2, oxygen saturation; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide.

CASE 3: SOPHIE

Delivery | Transport to NICU | Settings

This case study concerns Sophie.

CASE 3: SOPHIE

- Delivery
  - Sophie is a term baby (birth weight 4100g) delivered by forceps for arrest of descent in an outside hospital. There was meconium in the amniotic fluid and Sophie presents with respiratory distress, with Apgar scores of 1, 6 and 8
  - She requires positive pressure ventilation in the delivery room, followed by continuous positive airway pressure (CPAP)

- Sophie is transferred to the NICU
  - Settings: CPAP 6 cmH_2O; FiO_2 40%
  - Monitoring: pre- and post-ductal SpO_2 88/84%; tcpO_2 45 mmHg (6.0 kPa); tcpCO_2 39 mmHg (5.2 kPa)
  - A chest X-ray shows few diffuse patchy opacities

- Settings upon arrival at the NICU
  - CPAP is continued and FiO_2 is increased to 70%
  - Settings: CPAP 6 cmH_2O; FiO_2 70%
  - Monitoring: pre- and post-ductal SpO_2 85/80%; tcpO_2 40 mmHg (5.3 kPa); tcpCO_2 38 mmHg (5.1 kPa)

CPAP, continuous positive airway pressure; FiO_2, fraction of inspired oxygen; NICU, neonatal intensive care unit; SpO_2, oxygen saturation; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

CASE 3: SOPHIE

- **As increased FiO_2 does not improve hypoxemia, Sophie is intubated and started on ventilation**
  - Settings: PIP 38 cmH_2O; PEEP 6 cmH_2O; rate 60/min (assisted/controlled); FiO_2 70%; MAP 12 cmH_2O
  - Monitoring: Pre- and post-ductal SpO_2 85/75%; tcpO_2 35 mmHg (4.7 kPa); tcpCO_2 28 mmHg (3.7 kPa)
  - Oxygenation index: 24
- TCM values identify PPHN as the primary problem. The situation is severe (oxygenation index > 20)
- Sophie is started on **inhaled nitric oxide (iNO)**, 20 ppm, synchronised mechanical ventilation, sedated and airway suctioning is performed
  - Settings: PIP 25 mmHg, PEEP 6 cmH_2O, rate 40/min, FiO_2 45%
  - Monitoring: pre- and post-ductal SpO_2 98/95%; tcpO_2 71 mmHg (9.4 kPa); tcpCO_2 42 mmHg (5.6 kPa)
- Sophie is stabilised and can safely be transported

Sophie had mild meconium aspiration syndrome complicated by persistent PPHN. Spontaneous breathing allows for valid gas exchange (normal tcpCO_2) but the increased pulmonary vascular resistance causes right-to-left shunting, venous blood mixing and hypoxemia (low tcpO_2). A difference between pre- and post-ductal SpO_2 can point in this direction, but this was not clear-cut in this case. TCM allowed for identification of PPHN as the primary problem, recognising its severity by calculating the oxygenation index (>20) and starting iNO. At the same time, TCM of CO_2 allowed for detecting hyperventilation and preventing complications, such as pneumothorax or brain damage. TCM allowed for quick decisions and a stepwise approach, in the resource-limited context of neonatal transport.

CO_2, carbon dioxide; FiO_2, fraction of inspired oxygen; iNO, inhaled nitric oxide; MAP, mean airway pressure; PEEP, positive end expiratory pressure; PIP, peak inspiratory pressure; PPHN, persistent pulmonary hypertension of the newborn; SpO_2, oxygen saturation; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

THE OXYGENATION INDEX CAN BE CALCULATED USING tcpO_2

- The oxygenation index is an indicator of lung injury
- **Oxygenation index = $\frac{FiO_2\ (\%) \times MAP\ (cmH_20)}{pO_2 \text{ or } tcpO_2 (mmHg)}$**
- According to the Montreux definition of neonatal ARDS, the oxygenation index can be calculated using arterial or, if arterial values are unavailable, transcutaneous pO_2 values
- Oxygenation index thresholds for ARDS:
  - 4.0–7.9: mild ARDS
  - 8.0–15.9: moderate ARDS
  - ⩾ 16.0: severe ARDS

De Luca D, et al. *Lancet Respir Med.* 2017;5:657-666.

ARDS, acute respiratory distress syndrome; FiO_2, fraction of inspired oxygen; MAP, mean airway pressure; pO_2, oxygen partial pressure; tcpO_2, transcutaneous partial pressure of oxygen.

SUMMARY

tcpO_2 is influenced by both the respiratory and the circulatory status

TCM can result in rapid diagnosis of hypercapnia and quicker diagnosis and treatment of PDA, while limiting blood gas sampling

TCM can rapidly detect hyperventilation

- This is important as hypocapnia can be harmful

tcpCO_2 can guide rapid adjustment of delta pressure in HFV

TCM allows for quick decision making

TCM can be a valuable tool in the resource-limited context of neonatal transport

HFV, high frequency ventilation; PDA, patent ductus arteriosus; TCM, transcutaneous monitoring; tcpCO_2, transcutaneous partial pressure of carbon dioxide; tcpO_2, transcutaneous partial pressure of oxygen.

SUMMARY AND CLOSE

SUMMARY

In this presentation you have learnt more about TCM and blood gases in the NICU and PICU

- Preterm neonates are vulnerable to changes in blood gases
  - Both low and high concentrations of O_2 and CO_2 are associated with serious adverse outcomes
- TCM provides added value, as it allows for continuous, non-invasive monitoring of tc*p*O_2 and tc*p*CO_2, including accurate detection of hyperoxemia
- TCM is a valuable part of a personalised monitoring approach in unstable children and children requiring respiratory support
- Careful evaluation of the practical aspects of TCM is important, so potential adverse effects can be avoided and readings are correct

CO_2, carbon dioxide; NICU, neonatal intensive-care unit; O_2, oxygen; PICU, paediatric intensive-care unit; TCM, transcutaneous monitoring; tc*p*CO_2, transcutaneous partial pressure of carbon dioxide; tc*p*O_2, transcutaneous partial pressure of oxygen

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GLOSSARY

- Ag/AgCI, silver chloride electrode
- ARDS, acute respiratory distress syndrome
- BE, base excess
- BPD, bronchopulmonary dysplasia
- CME, continuing medical education
- CO_2, carbon dioxide
- CPAP, continuous positive airway pressure
- ctO_2, total oxygen concentration
- ESPNIC, European Society for Paediatric and Neonatal Intensive Care
- ESPR, European Society for Paediatric Research
- $EtCO_2$, partial pressure of end-tidal carbon dioxide
- FiO_2, fraction of inspired oxygen
- HbF, foetal haemoglobin
- HbO_2, oxyhaemoglobin
- HVF, high frequency ventilation
- MAP, mean airway pressure
- NEC, necrotising enterocolitis
- NICU, neonatal intensive-care unit
- O_2, oxygen
- PAH, pulmonary arterial hypertension
- pCO_2, partial pressure of carbon dioxide
- PDA, patent ductus arteriosus
- PEEP, positive end expiratory pressure
- PICU, paediatric intensive-care unit
- PIP, peak inspiratory pressure
- pO_2, partial pressure of oxygen
- PPHN, persistent pulmonary hypertension of the newborn
- RDS, respiratory distress syndrome
- ROP, retinopathy of prematurity
- RSV, respiratory syncytial virus
- TC, transcutaneous
- TCb, transcutaneous bilirubinometry
- TCM, transcutaneous monitoring
- $tcpCO_2$, transcutaneous partial pressure of carbon dioxide
- $tcpO_2$, transcutaneous partial pressure of oxygen
- SpO_2, oxygen saturation

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