



BLOOD GASES AND TRANSCUTANEOUS MONITORING IN THE NICU AND PICU





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 [$tc\dot{p}CO_2$]) and oxygen [$tc\dot{p}O_2$])
 - 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

SCIENTIFIC COMMITTEE

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

Daniele de Luca, MD, PhD

**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

Olivier Danhaive, 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

Kaare E. Lundstrøm, MD

**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

Anton van Kaam, MD, PhD



CONTENT

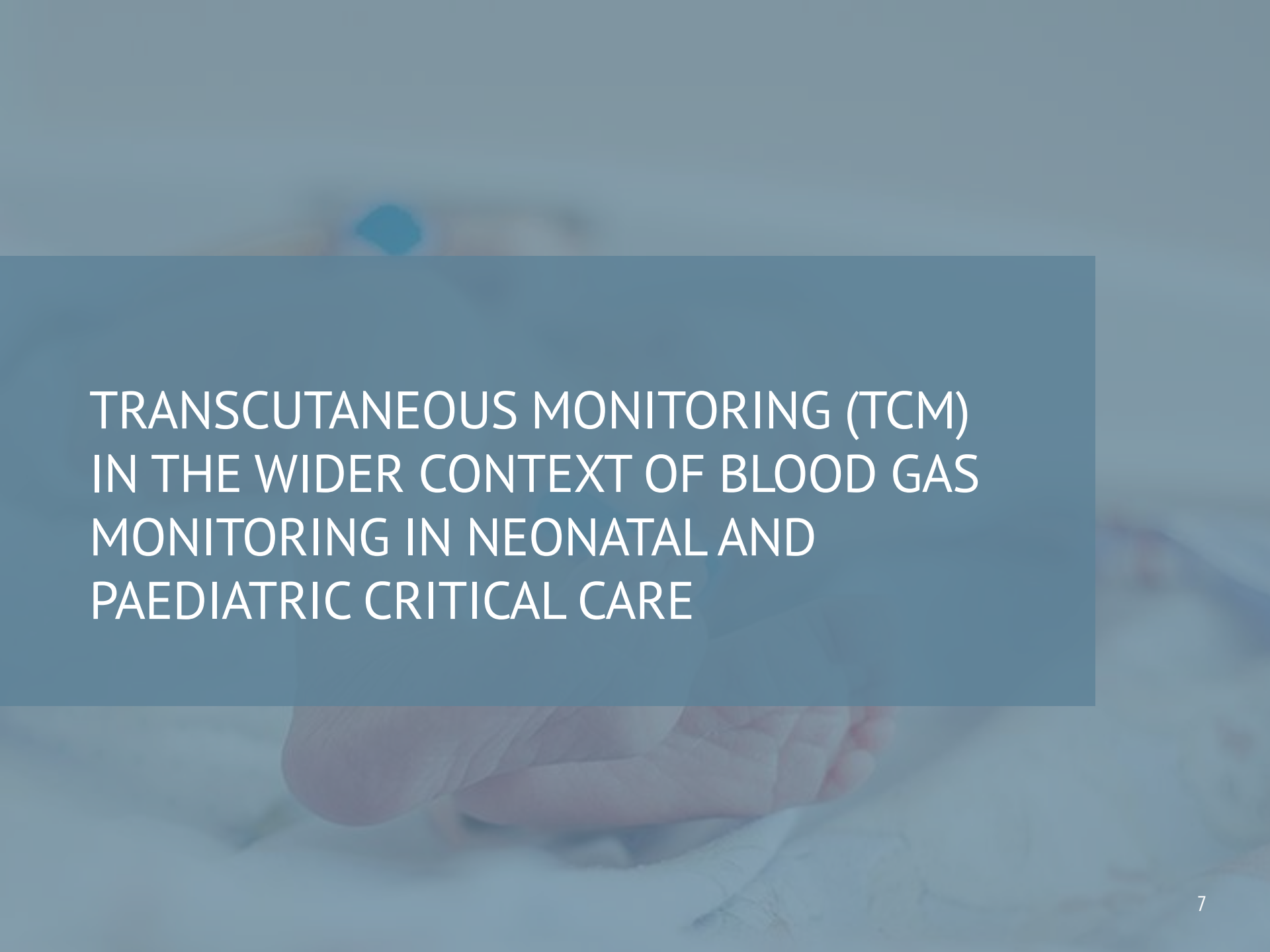
TCM IN THE WIDER CONTEXT OF BLOOD GAS MONITORING IN NEONATAL AND PAEDIATRIC CRITICAL CARE; THE ADDED VALUE OF TCM PARAMETERS

INDICATIONS FOR TCM IN NEONATAL AND PAEDIATRIC CRITICAL CARE

PRACTICAL ASPECTS OF TCM TECHNOLOGY IN NEONATOLOGY

INTERPRETATION OF THE RESULTS OF TCM

SUMMARY



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 life¹⁻³
- Preterm neonates are vulnerable to changes in blood gas values

PRETERM NEONATES ARE VULNERABLE TO CHANGES IN BLOOD GAS VALUES

High oxygen partial pressure (pO_2)

- Oxidative damage¹ is associated with
 - Acute lung injury and bronchopulmonary dysplasia (BPD)²
 - Retinopathy of prematurity (ROP)³
 - White matter injury¹
 - Oxygen organ toxicity⁴

High carbon dioxide partial pressure (pCO_2)

- Increased mortality⁹

Low pO_2

- Centralised blood flow to brain and heart is associated with an increased incidence of
 - Necrotising enterocolitis (NEC)³
 - Acute kidney failure⁵
- Pulmonary arterial hypertension (PAH)⁶
- Impaired neurological development⁷
- Increased mortality⁸

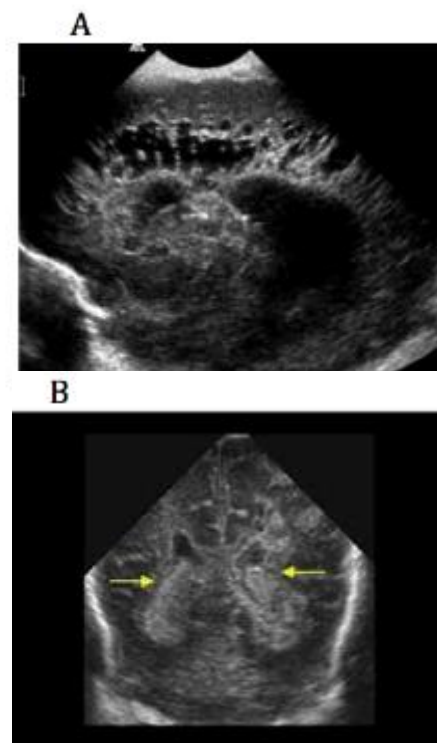
Low pCO_2

- Associated with increased incidence of BPD^{2,10}
- Causes reduction in cerebral blood flow¹⁰
 - Increased risk of ischemia
 - Increased risk of white matter injury
 - Increased risk of adverse neurologic outcome
- Limits cerebral metabolism¹⁰

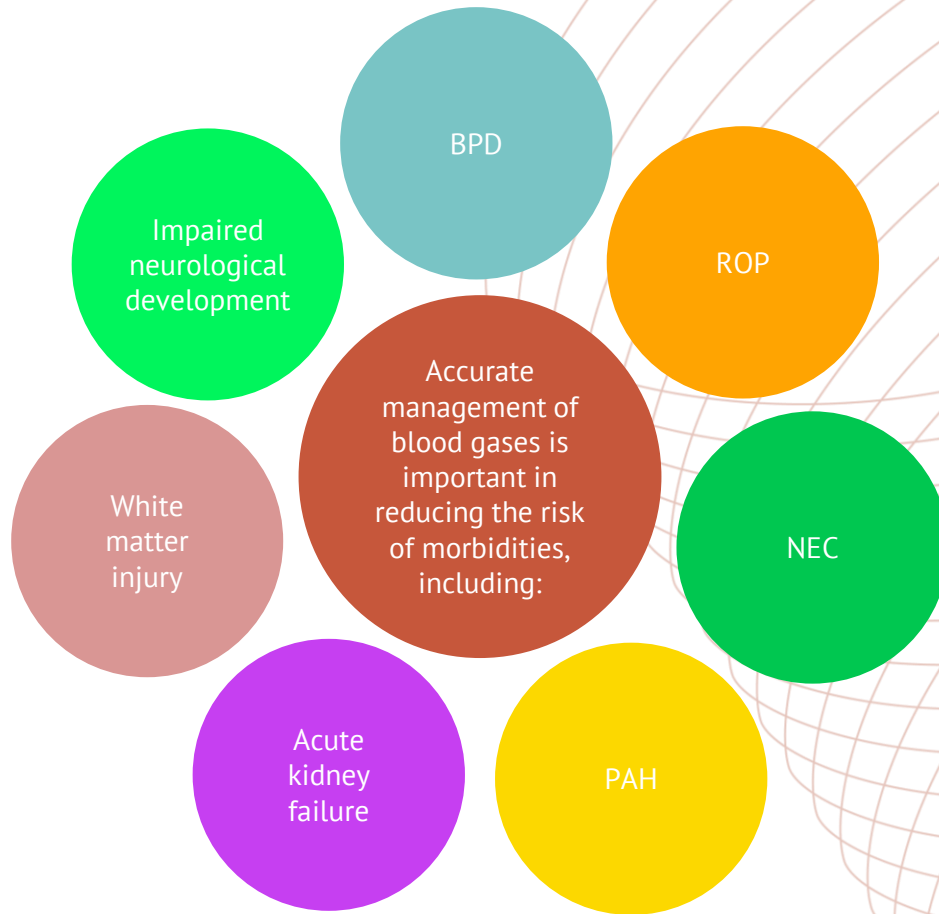
THE IMPORTANCE OF BLOOD GAS MONITORING: THE ROLE OF CO₂ AND O₂ IN THE CEREBRAL CIRCULATION

	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 pCO₂** (hyperventilation) or **high pO₂** (uncontrolled hyperoxemia) levels increase the risk for preterm infants of ischemic lesions, such as periventricular leukomalacia (A) or white matter injury
- Similarly, **low pO₂** (respiratory failure, insufficient ventilatory support) may predispose to cerebral haemorrhage (B)
 - No association between high pCO₂ and brain damage has been demonstrated
- **This stresses the importance of close monitoring of blood gases in preterm infants**



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



TCM in the wider context of blood gas monitoring in neonatal and paediatric critical care

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

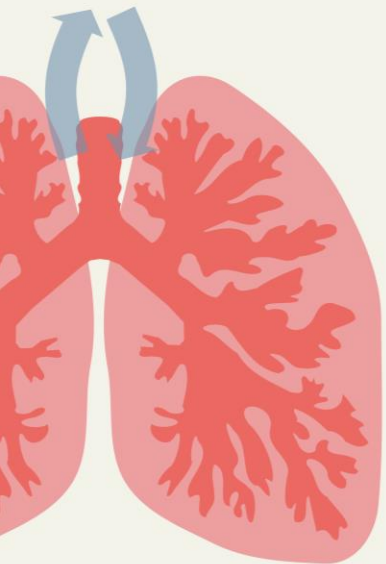
Airways



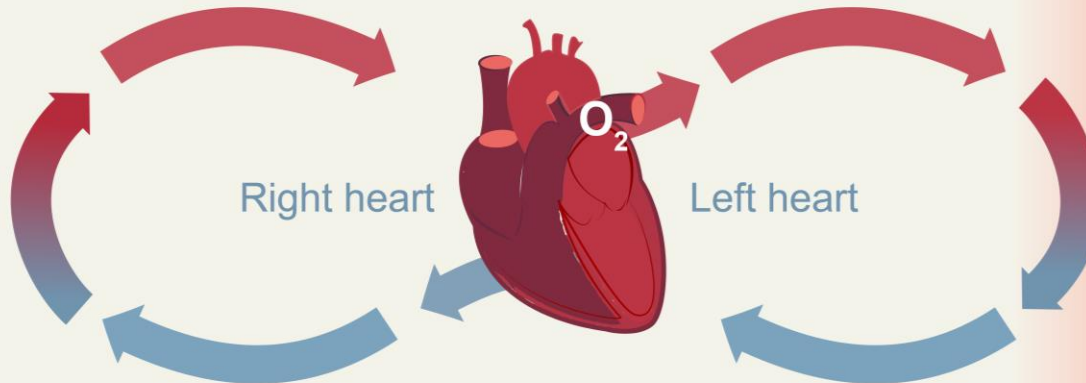
Arterial blood



Capillary blood



- End-tidal monitoring of $p\text{CO}_2$

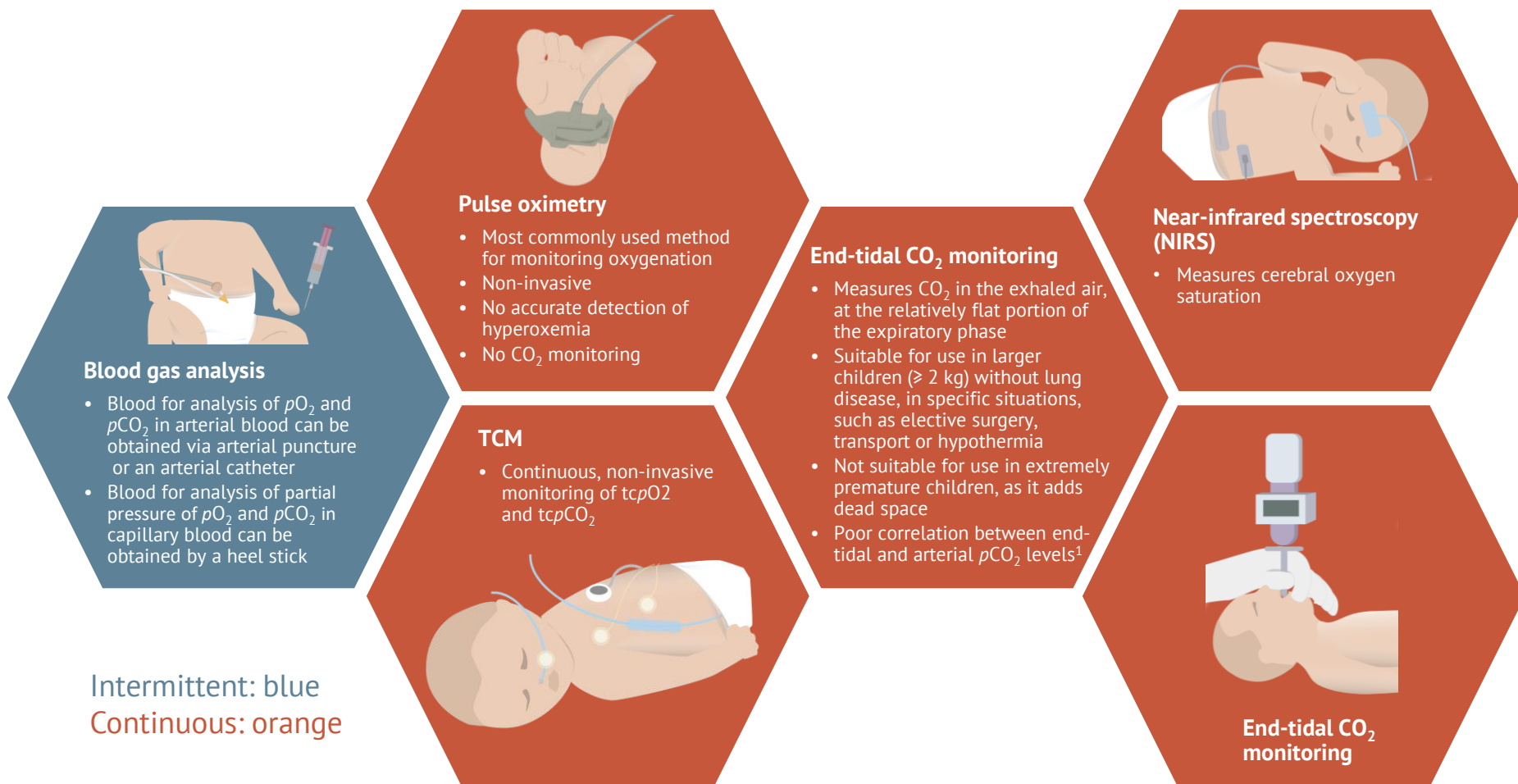


- Blood gas analysis of $p\text{O}_2$ and $p\text{CO}_2$ in arterial blood
- Pulse oximetry to monitor O_2 saturation

- Blood gas analysis of $p\text{O}_2$ and $p\text{CO}_2$ in capillary blood
- TCM of $p\text{O}_2$ and $p\text{CO}_2$

O_2 , oxygen; $p\text{CO}_2$, carbon dioxide partial pressure; $p\text{O}_2$, oxygen partial pressure.

BLOOD GASES CAN BE MONITORED INTERMITTENTLY OR CONTINUOUSLY



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

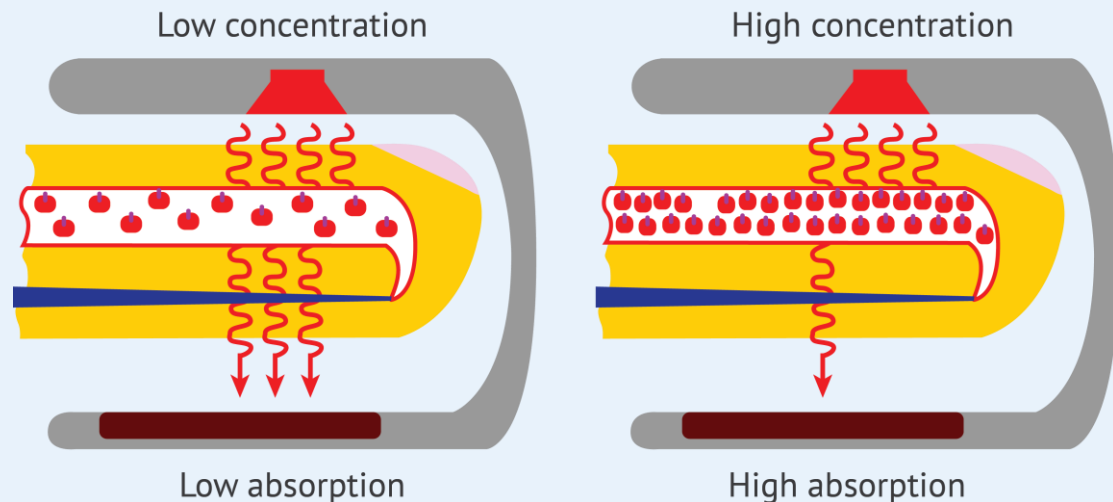
PULSE OXIMETRY MONITORS OXYGENATION

Pulse oximetry monitors oxygenation

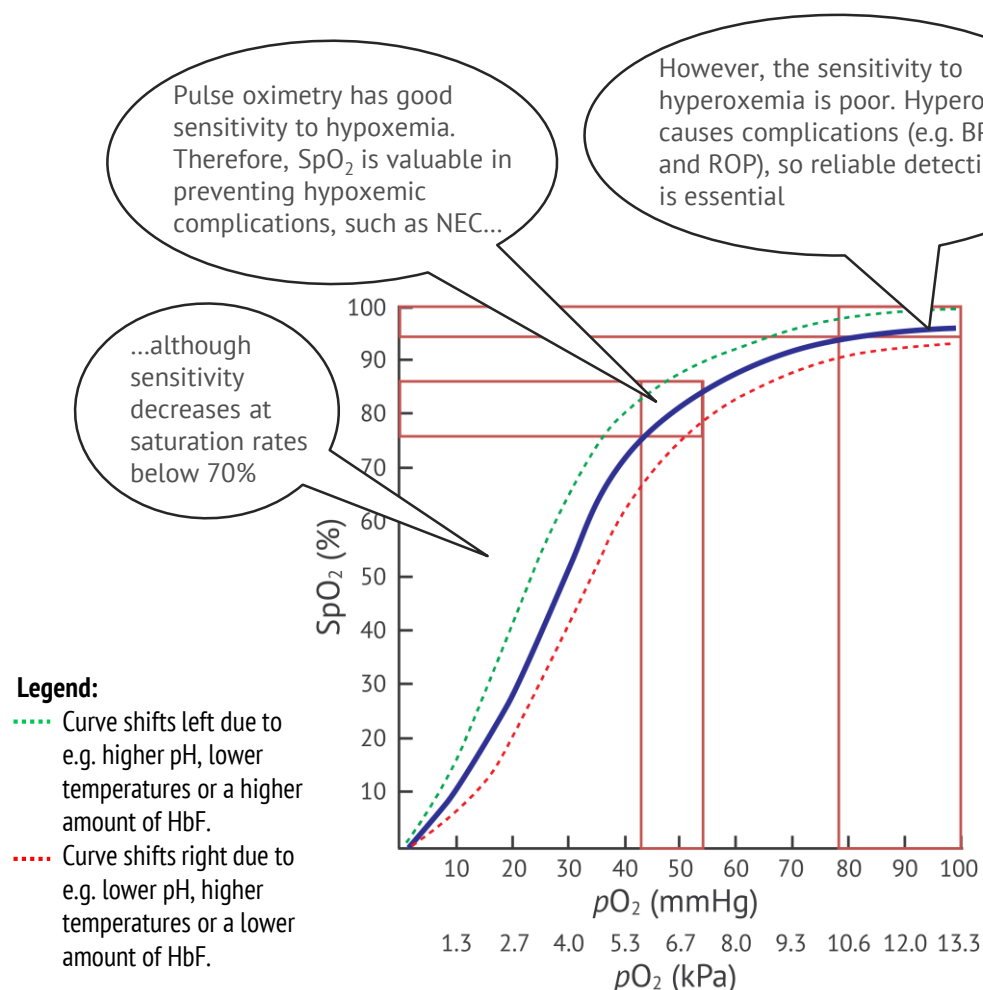
- The device measures the light absorption of oxyhaemoglobin (HbO_2) and deoxyhaemoglobin
- Oxygen saturation (SpO_2) is reported as a percentage
 - $\text{HbO}_2 / (\text{HbO}_2 + \text{deoxyhaemoglobin})$

Pulse oximetry is non-invasive and easy to use

HOW PULSE OXIMETRY WORKS



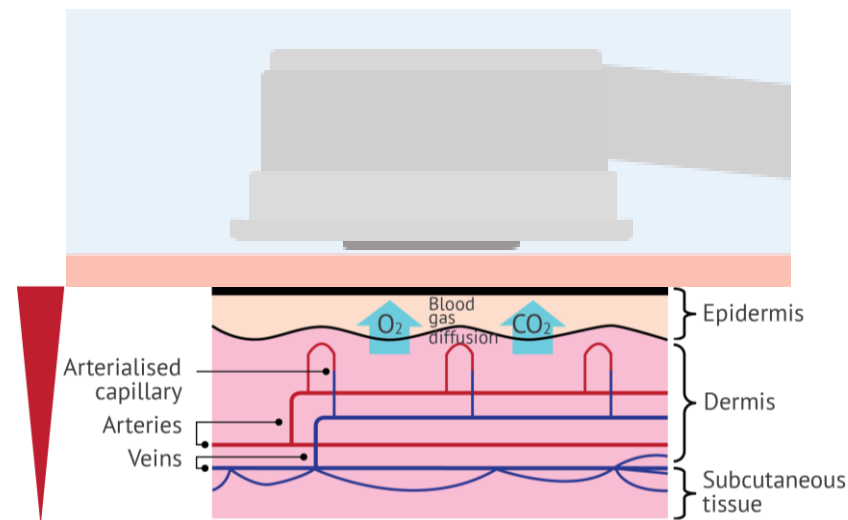
PULSE OXIMETRY ALONE CANNOT BE USED TO PREVENT COMPLICATIONS OF HYPEROXEMIA



- 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 because of the wide variation of partial pressure of oxygen values associated with oxygen saturation values > 95%

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



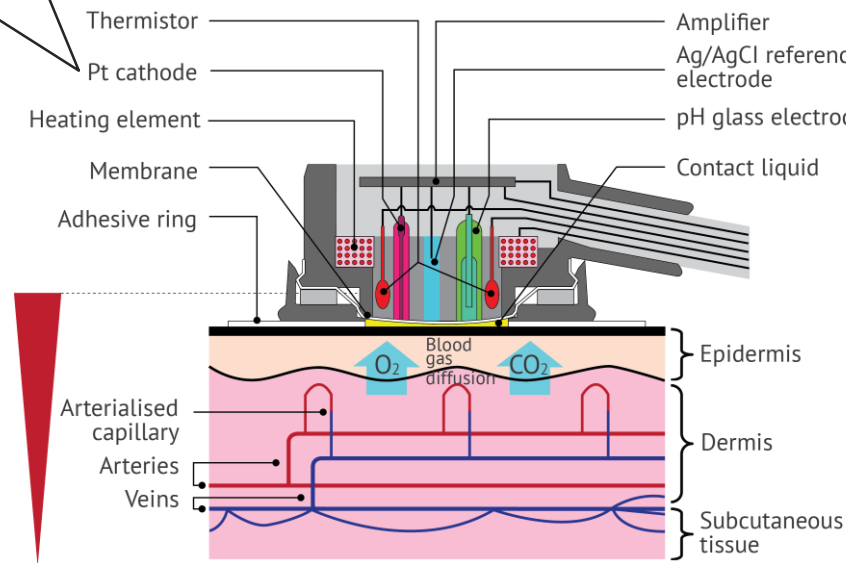
TECHNOLOGY PRINCIPLE OF TCM

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

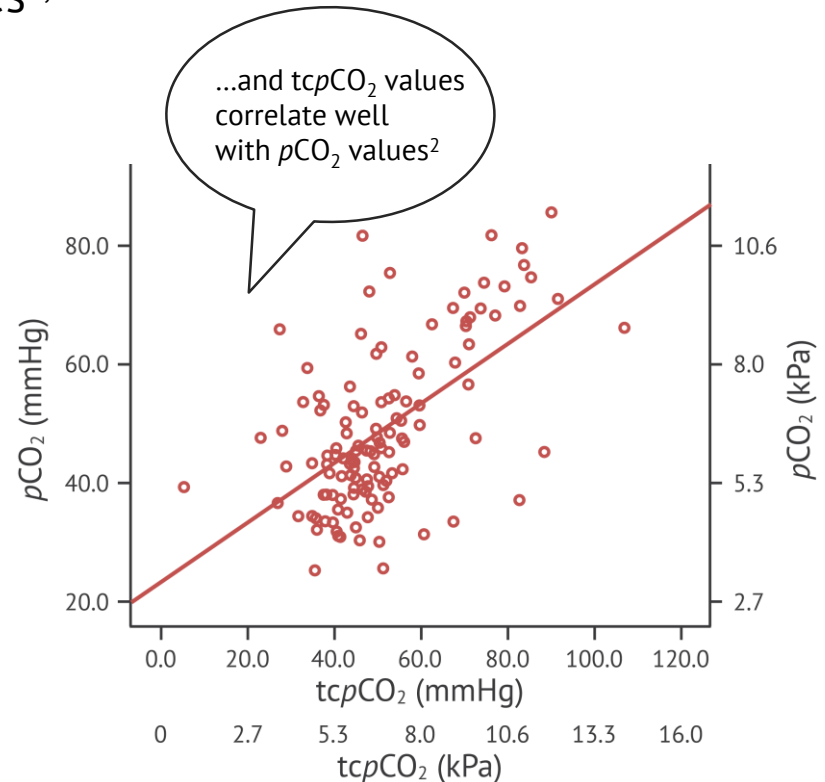
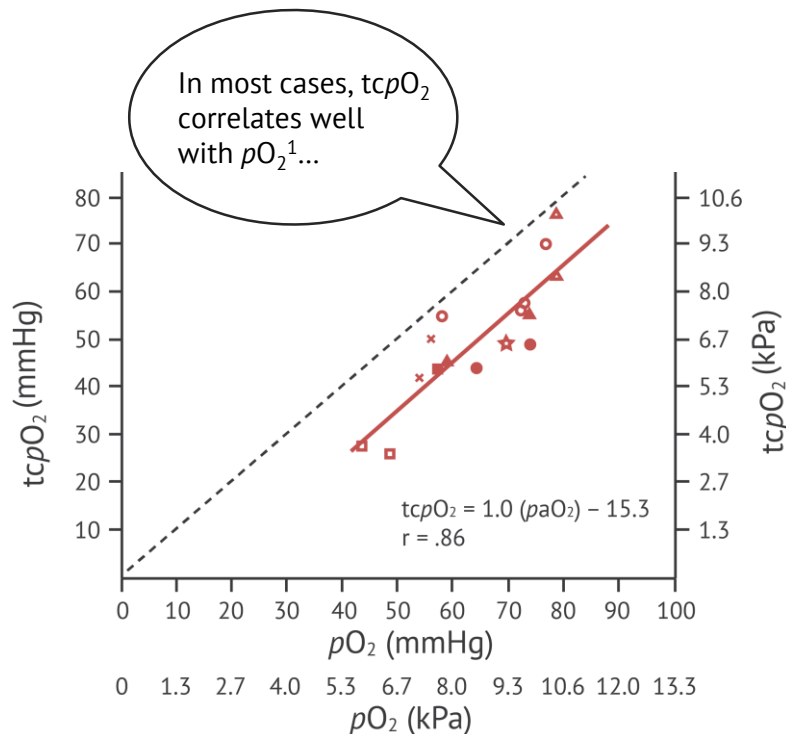
CO_2 reacts with water forms carbonic acid and dissociates into H^+ which are interpreted through a pH glass element. After conversion, the sensor algorithm generates a $tcpCO_2$ in mmHg or kPa.



TCM in the wider context of blood gas monitoring in neonatal and paediatric critical care

$tcpO_2/tcpCO_2$ 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}



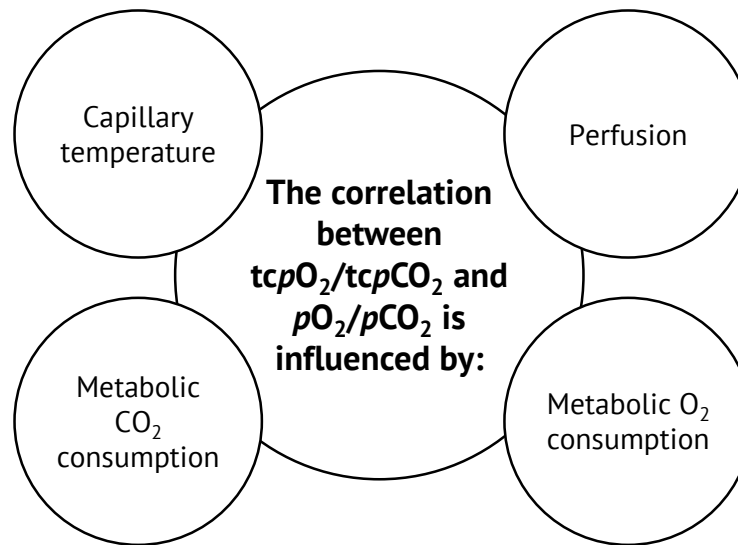
1. Used with permission from: Rome ES, et al. *Pediatrics*. 1984;74:217-20. 2. Used with permission from: Aly S, et al. *Am J Perinatol*. 2017;34:480-5.

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.

TCM in the wider context of blood gas monitoring in neonatal and paediatric critical care

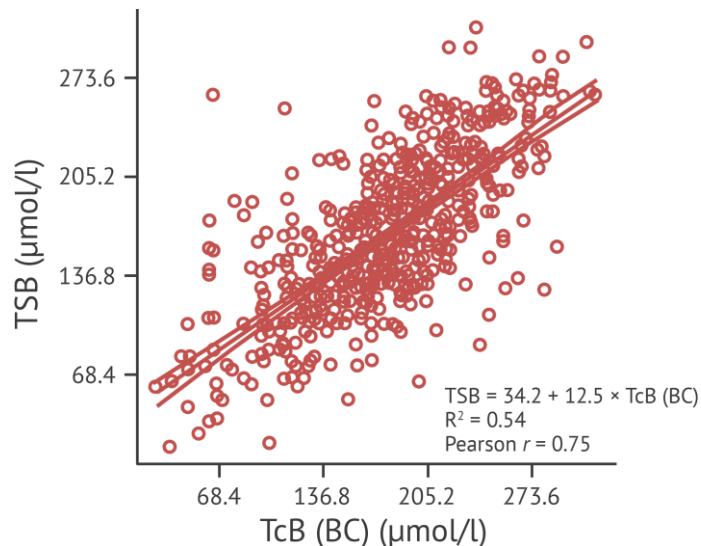
$tcpO_2/tcpCO_2$ AND pO_2/pCO_2 ARE STRONGLY RELATED, BUT TELL A DIFFERENT STORY

- 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**



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



TCM in the wider context of blood gas monitoring in neonatal and paediatric critical care

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 analysis¹, 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; EtCO₂, partial pressure of end-tidal carbon dioxide; Hb, haemoglobin; pO₂, oxygen partial pressure; ROP, retinopathy of prematurity; SpO₂, oxygen saturation; TCM, transcutaneous monitoring; tcpCO₂, transcutaneous partial pressure of carbon dioxide; tcpO₂, 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

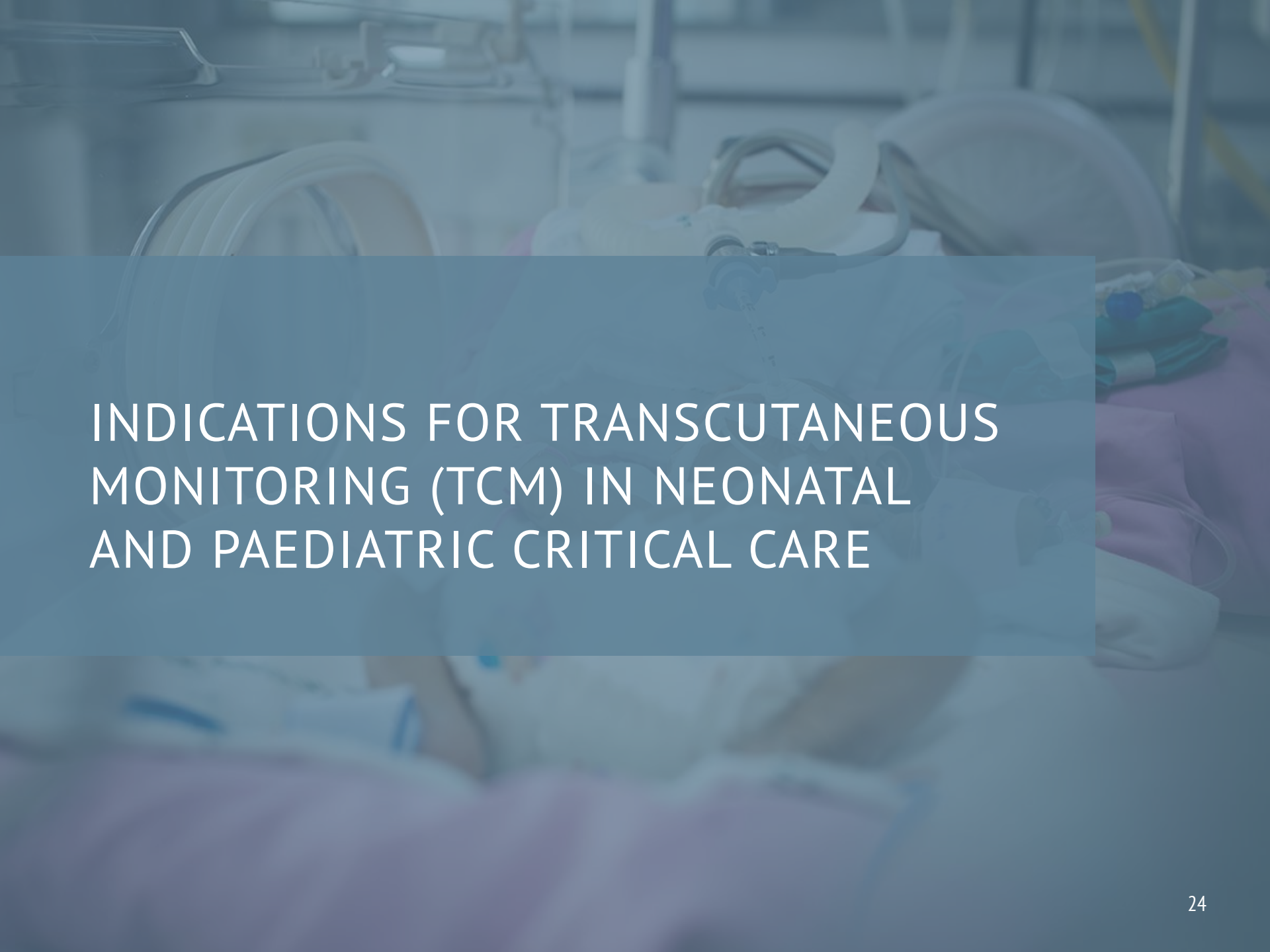
SUMMARY (continued)

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 measurement¹, 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

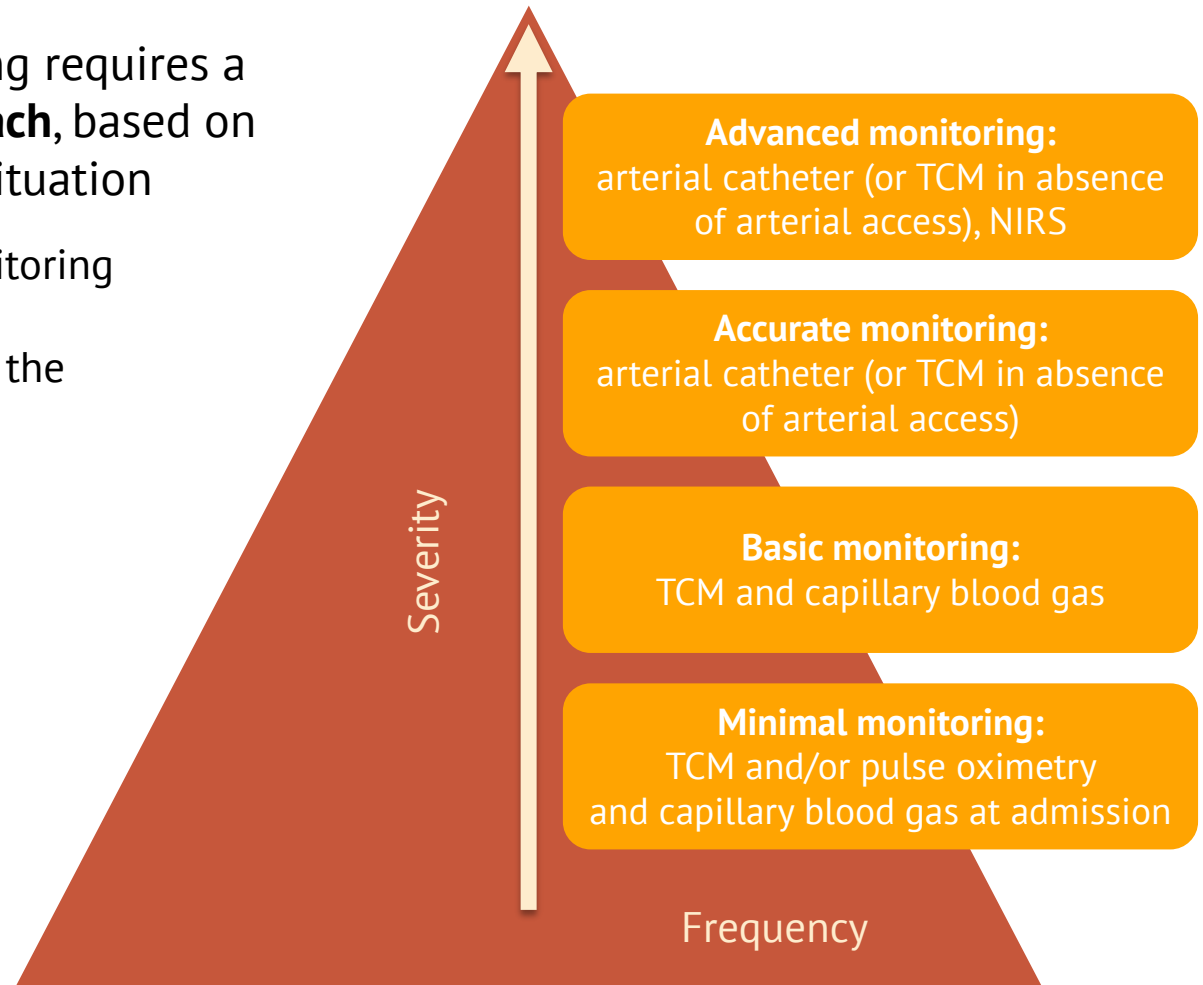
LEARNING OBJECTIVE

- 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

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



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

tcpO₂ provides information on **oxygenation**

- In children on **mechanical ventilation**, tcpO₂ is useful for managing ventilatory pressures and lung volume, escalating and weaning
- tcpO₂ 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)
- tcpO₂ monitoring can be useful to prevent hyperoxemia during **procedures**, such as **surfactant** administration or pneumothorax drainage

tcpCO₂ provides information on **ventilation**

- In children on **mechanical ventilation**, tcpCO₂ 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
- tcpCO₂ can also be useful in **spontaneously breathing children**, e.g. during transport, following procedures or in patients who are otherwise **unstable**
- tcpCO₂ measurement can be valuable during administration of **surfactant**, as surfactant may cause transient hypercapnia

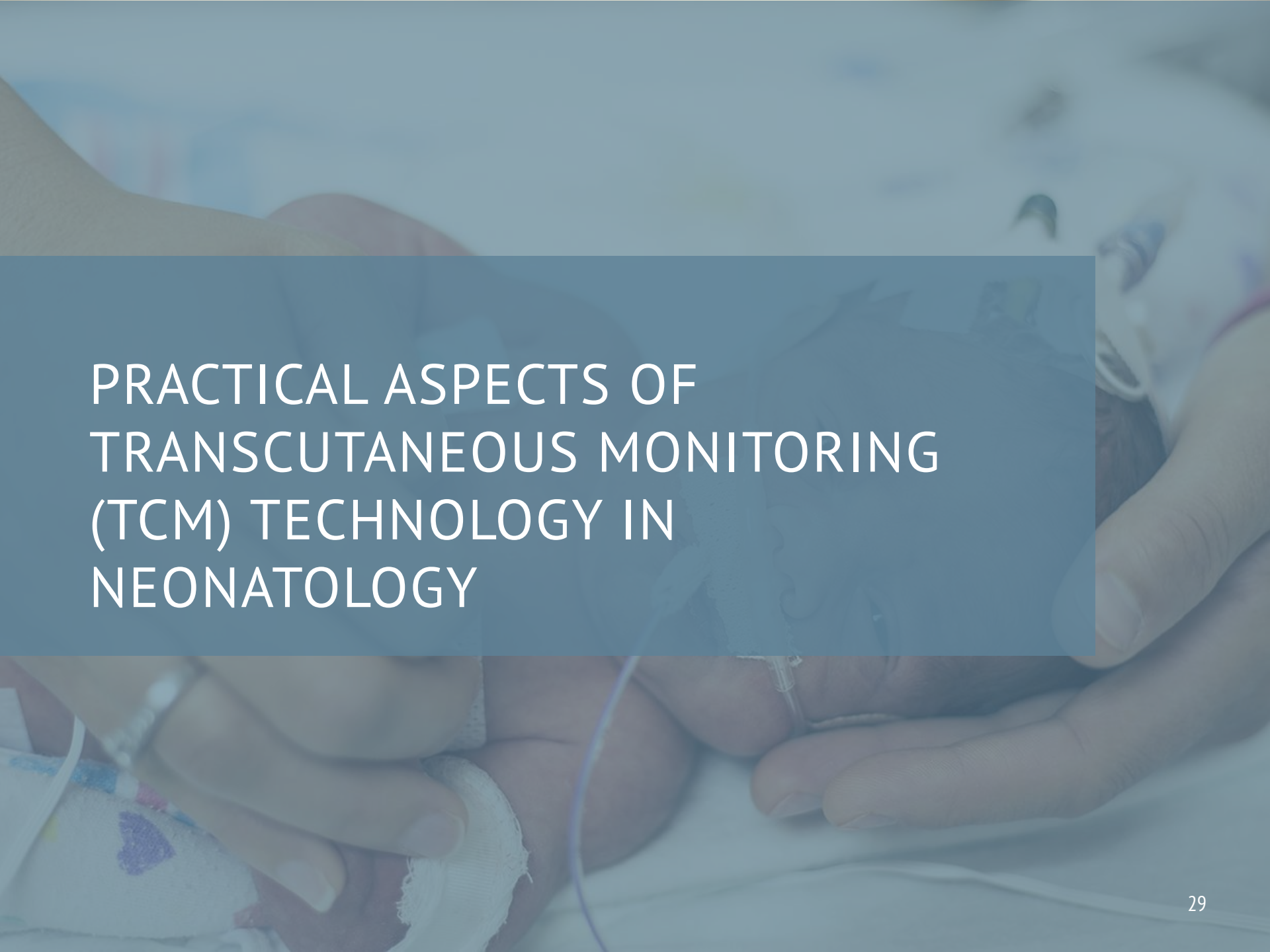
SUMMARY

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

- $tc\text{pO}_2$ provides information on oxygenation
- $tc\text{pCO}_2$ provides information on ventilation



PRACTICAL ASPECTS OF TRANSCUTANEOUS MONITORING (TCM) TECHNOLOGY IN NEONATOLOGY

INTRODUCTION

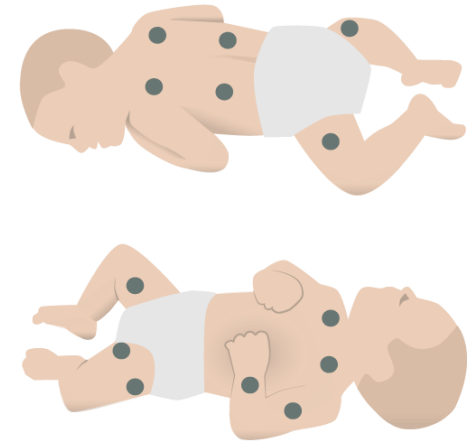
LEARNING OBJECTIVE

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

This section focuses on the clinical user's perspective

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 $tc\dot{p}O_2$ and underestimating $tc\dot{p}CO_2$ 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 $tc\dot{p}CO_2$ and around 10 minutes for $tc\dot{p}O_2$ 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



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 pCO₂
	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 pO₂ - Can be used for calculating oxygenation index
Limitations		- Low temperature limits accuracy for tcpO₂ - Longer stabilisation time for tcpCO₂	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

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°C¹
- 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

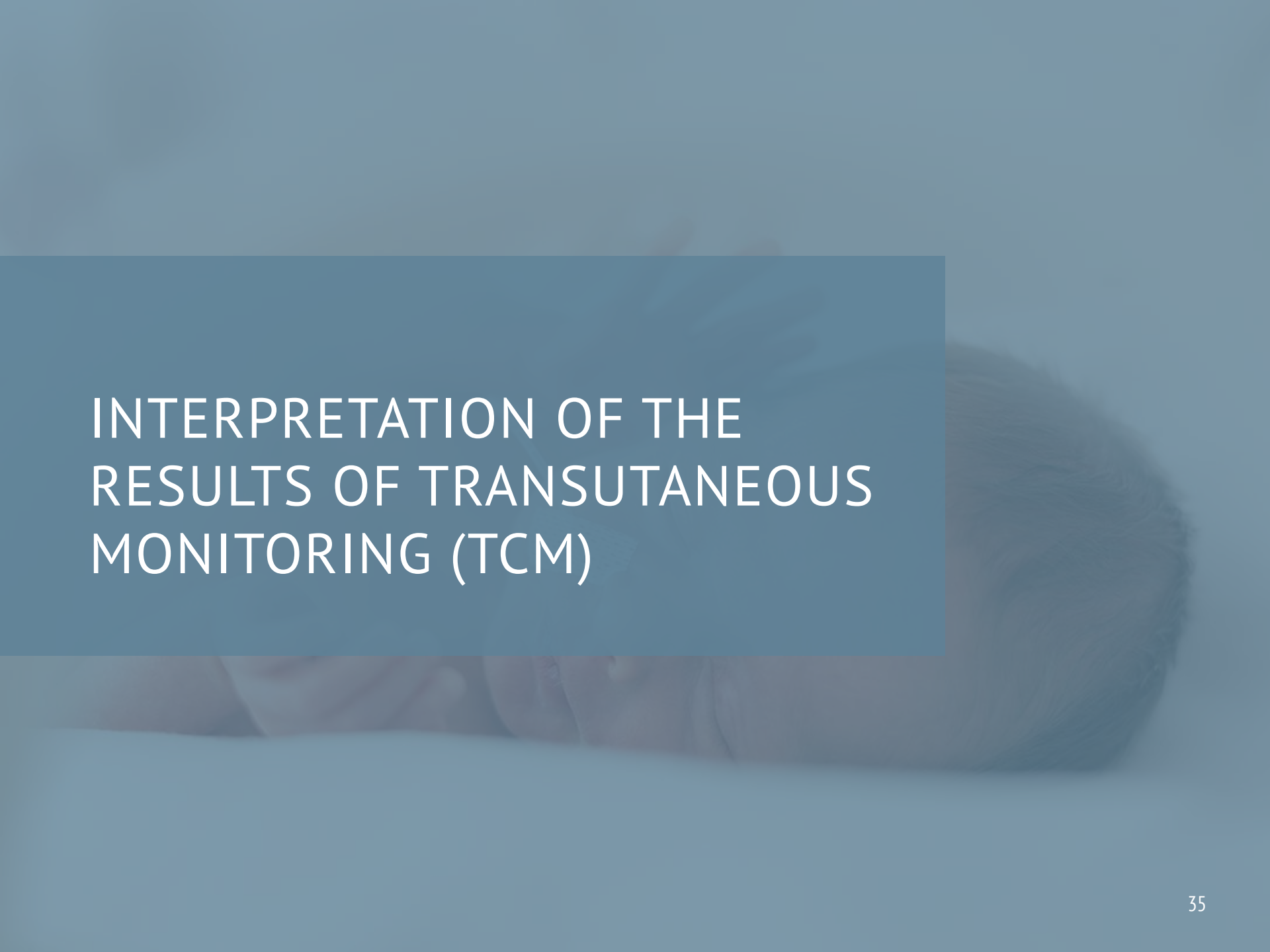
- The sensor must be in full contact with the skin
- Initiation of TCM involves calibration and sensor stabilisation time

Sensor temperatures have specific indications and practical considerations

- The optimal sensor temperature for reliable measurement of $tc\dot{p}O_2$ and $tc\dot{p}CO_2$ is $\geq 43^\circ C$
- 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



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

CASE 1: LIZZY

Admission

Initial monitoring

Subsequent monitoring



Lizzy

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

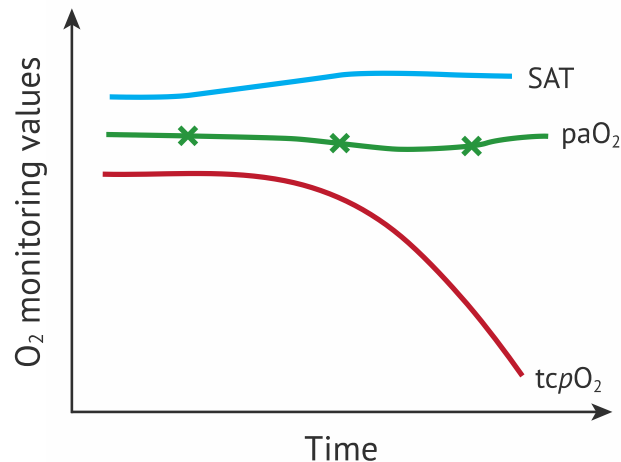
- After intubation, Lizzy initially has stable, acceptable values:
 - Heart rate 110-120/min
 - Blood pressure around 90/60 mmHg
 - SpO_2 94-96%
 - $tcpO_2$ 60-67.5 mmHg (8-9 kPa)
 - $tcpCO_2$ 45-48.75 mmHg (6-6.5 kPa)

• 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

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

CASE 2: JOE AND MIKE

Admission

Initial monitoring

Subsequent monitoring



Joe & Mike

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 cmH₂O
 - Positive end expiratory pressure (PEEP) 6 cmH₂O
 - Rate 60/min
 - Inspiration time 0.35 sec
 - FiO₂ 35%

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. tcpO₂ 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 ₂ O.
10 am		Increased PIP only results in modest changes in tcpCO₂. 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 ₂ O.	
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.

CASE 2: JOE AND MIKE

- Joe and Mike are both set up on HFV, with the following initial settings:
 - MAP 15 cmH₂O
 - Delta pressure 27 cmH₂O, as this shows clear chest vibrations
 - Frequency 10 Hz
 - FiO₂ 50%

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. tcpCO₂ < 30 mmHg (4 kPa) → delta pressure reduced to 25 cmH ₂ O.
11.30 am		tcpCO₂ 30 mmHg (4 kPa) → delta pressure reduced to 22 cmH ₂ O.
12 am		tcpCO₂ 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 ₂ O.	
10 pm	Blood gas analysis to assess effect of decrease in delta pressure shows: pH 7.46, PaCO ₂ 29.25 mmHg (3.9 kPa), BE -5.1 mmol/L. Still hypocapnia → delta pressure reduced to 22 cmH ₂ O.	
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 tcpCO₂-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.

CASE 3: SOPHIE

Delivery

Transport to NICU

Settings



Sophie

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 cmH₂O; FiO₂ 40%
- Monitoring: pre- and post-ductal SpO₂ 88/84%; tcpO₂ 45 mmHg (6.0 kPa); tcpCO₂ 39 mmHg (5.2 kPa)
- A chest X-ray shows few diffuse patchy opacities

- Settings upon arrival at the NICU

- CPAP is continued and FiO₂ is increased to 70%
- Settings: CPAP 6 cmH₂O; FiO₂ 70%
- Monitoring: pre- and post-ductal SpO₂ 85/80%; tcpO₂ 40 mmHg (5.3 kPa); tcpCO₂ 38 mmHg (5.1 kPa)

CASE 3: SOPHIE

- **As increased FiO_2 does not improve hypoxemia, Sophie is intubated and started on ventilation**
 - Settings: PIP 38 cmH₂O; PEEP 6 cmH₂O; rate 60/min (assisted/controlled); FiO_2 70%; MAP 12 cmH₂O
 - 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 cmH₂O, 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.

THE OXYGENATION INDEX CAN BE CALCULATED USING $tcpO_2$

- The oxygenation index is an indicator of lung injury
- **Oxygenation index = $\frac{FiO_2 (\%) \times MAP (cmH_2O)}{pO_2 \text{ or } tcpO_2 (mmHg)}$**
- 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

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



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 $tcpO_2$ and $tcpCO_2$, 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

REFERENCES

- Aly S, et al. Transcutaneous carbon dioxide monitoring with reduced-temperature probes in very low birth weight infants. *Am J Perinatol*. 2017;34:480-5.
- Ambalavanan N, et al. Hypocapnia and hypercapnia in respiratory management of newborn infants. *Clin Perinatol*. 2001;28:517-31.
- Askie LM, et al. Effects of targeting lower versus higher arterial oxygen saturations on death or disability in preterm infants. *Cochrane Database Syst Rev*. 2017;4:CD011190.
- BOOST II United Kingdom, Australia, and New Zealand Collaborative Groups. Oxygen saturation and outcomes in preterm infants. *N Engl J Med*. 2013;368:2094-104.
- Collins JA, et al. Relating oxygen partial pressure, saturation and content: the haemoglobin-oxygen dissociation curve. *Breathe (Sheff)*. 2015;11:194-201.
- Colombo B, et al. The pattern of fetal haemoglobin disappearance after birth. *Br J Haematol*. 1976;32:79-87.
- Danhaive O, et al. Pulmonary hypertension and right ventricular dysfunction in growth-restricted, extremely low birth weight neonates. *J Perinatol*. 2005;25:495-9.
- De Luca D, et al. The Montreux definition of neonatal ARDS: biological and clinical background behind the description of a new entity. *Lancet Respir Med*. 2017;5:657-66.
- De Luca D, et al. Monitorages physiopathologiques en réanimation néonatale (Biomonitoring in neonatal critical care). *J Pédiatrie Puériculture*. 2015;28:276-300.
- De Luca D, et al. Attempt to improve transcutaneous bilirubinometry: a double-blind study of Medick BiliMed versus Respironics BiliCheck. *Arch Dis Child Fetal Neonatal Ed*. 2008;93:F135-9.
- Erickson SJ, et al. Hypocarbia in the ventilated preterm infant and its effect on intraventricular haemorrhage and bronchopulmonary dysplasia. *J Paediatr Child Health*. 2002;38:560-2.
- Graziani LJ, et al. Mechanical ventilation in preterm infants: neurosonographic and developmental studies. *Pediatrics*. 1992;90:515-22.
- Hughes JMB. Pulmonary gas exchange. *Eur Respir Mon*. 2005;31:106-26.
- Husain-Syed F, et al. Lung-Kidney Cross-Talk in the Critically Ill Patient. *Am J Respir Crit Care Med*. 2016;194:402-14.
- Johnson S, et al. Neurodevelopmental outcomes following late and moderate prematurity: a population-based cohort study. *Arch Dis Child Fetal Neonatal Ed*. 2015;100:F301-8.
- Johnson S, et al. Learning disabilities among extremely preterm children without neurosensory impairment: Comorbidity, neuropsychological profiles and scholastic outcomes. *Early Hum Dev*. 2016;103:69-75.
- Marlow N, et al. Neurologic and developmental disability at six years of age after extremely preterm birth. *N Engl J Med*. 2005 6;352:9-19.

REFERENCES

- Mukhopadhyay S, et al. Neonatal transcutaneous carbon dioxide monitoring--effect on clinical management and outcomes. *Respir Care*. 2016;61:90-7.
- Northway WH. Bronchopulmonary dysplasia: then and now. *Arch Dis Child*. 1990;65(10 Spec No):1076-81.
- Perrone S, et al. Oxygen use in neonatal care: a two-edged sword. *Front Pediatr*. 2017;4:143.
- Pryds O, et al. Effect of PaCO₂ and haemoglobin concentration on day to day variation of CBF in preterm neonates. *Acta Paediatr Scand Suppl*. 1989;360:33-6.
- Rome ES, et al. Limitations of transcutaneous PO₂ and PCO₂ monitoring in infants with bronchopulmonary dysplasia. *Pediatrics*. 1984;74:217-20.
- Sola A, et al. Safe oxygen saturation targeting and monitoring in preterm infants: can we avoid hypoxia and hyperoxia? *Acta Paediatr*. 2014;103:1009-18.
- Sørensen LC, et al. Effects of the transcutaneous electrode temperature on the accuracy of transcutaneous carbon dioxide tension. *Scand J Clin Lab Invest*. 2011;71:548-52.
- Sweet DG, et al. European consensus guidelines on the management of respiratory distress syndrome - 2016 update. *Neonatology*. 2017;111:107-25.
- Thome UH, et al. Influence of PCO₂ control on clinical and neurodevelopmental outcomes of extremely low birth weight infants. *Neonatology*. 2018;113:221-30.
- Tobias JD, et al. Noninvasive monitoring of carbon dioxide during respiratory failure in toddlers and infants: end-tidal versus transcutaneous carbon dioxide. *Anesth Analg*. 1997;85:55-8.
- Yoon S, et al. pCO₂ and pH regulation of cerebral blood flow. *Front Physiol*. 2012;3:365.

GLOSSARY

- Ag/AgCl, silver chloride electrode
- ARDS, acute respiratory distress syndrome
- BE, base excess
- BPD, bronchopulmonary dysplasia
- CME, continuing medical education
- CO₂, carbon dioxide
- CPAP, continuous positive airway pressure
- ctO₂, total oxygen concentration
- ESPNIC, European Society for Paediatric and Neonatal Intensive Care
- ESPR, European Society for Paediatric Research
- EtCO₂, partial pressure of end-tidal carbon dioxide
- FiO₂, fraction of inspired oxygen
- HbF, foetal haemoglobin
- HbO₂, oxyhaemoglobin
- HVF, high frequency ventilation
- MAP, mean airway pressure
- NEC, necrotising enterocolitis
- NICU, neonatal intensive-care unit
- O₂, oxygen
- PAH, pulmonary arterial hypertension
- pCO₂, partial pressure of carbon dioxide
- PDA, patent ductus arteriosus
- PEEP, positive end expiratory pressure
- PICU, paediatric intensive-care unit
- PIP, peak inspiratory pressure
- pO₂, 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
- tcpCO₂, transcutaneous partial pressure of carbon dioxide
- tcpO₂, transcutaneous partial pressure of oxygen
- SpO₂, oxygen saturation



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