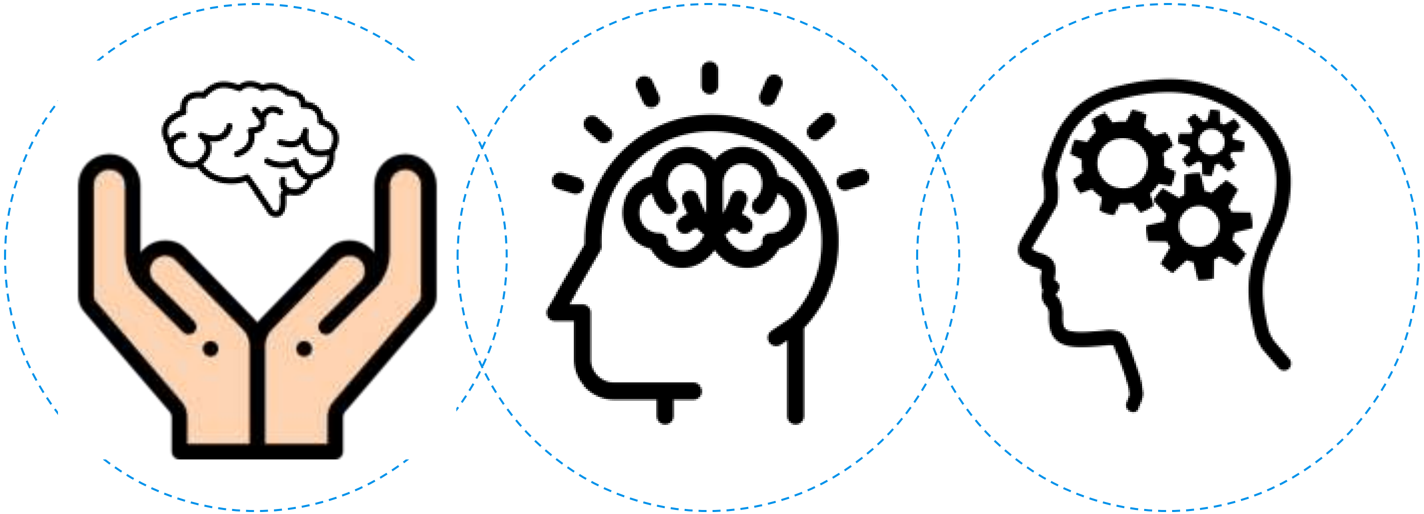
Neuromonitoring in the PICU

What do we mean by Neuro-monitoring?

What do we mean by neuromonitoring?



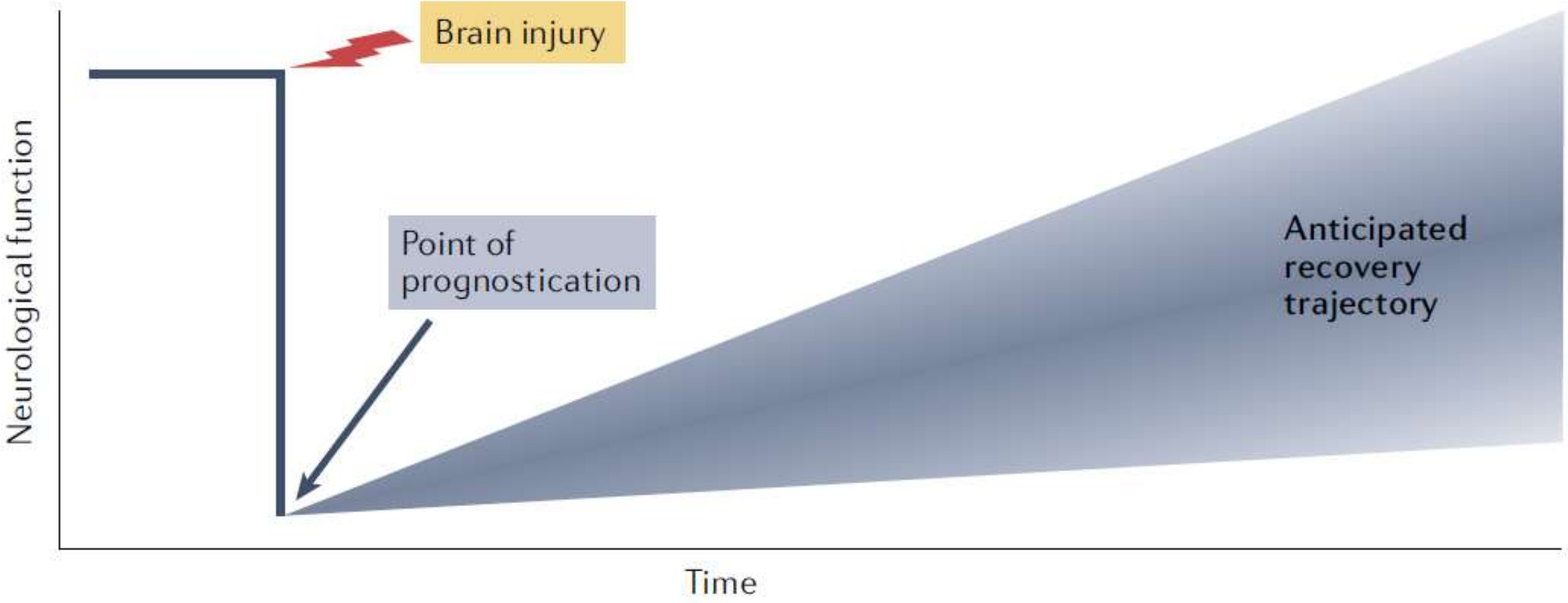
Clinical Monitoring

Cerebral Activity

Neuroprognostication

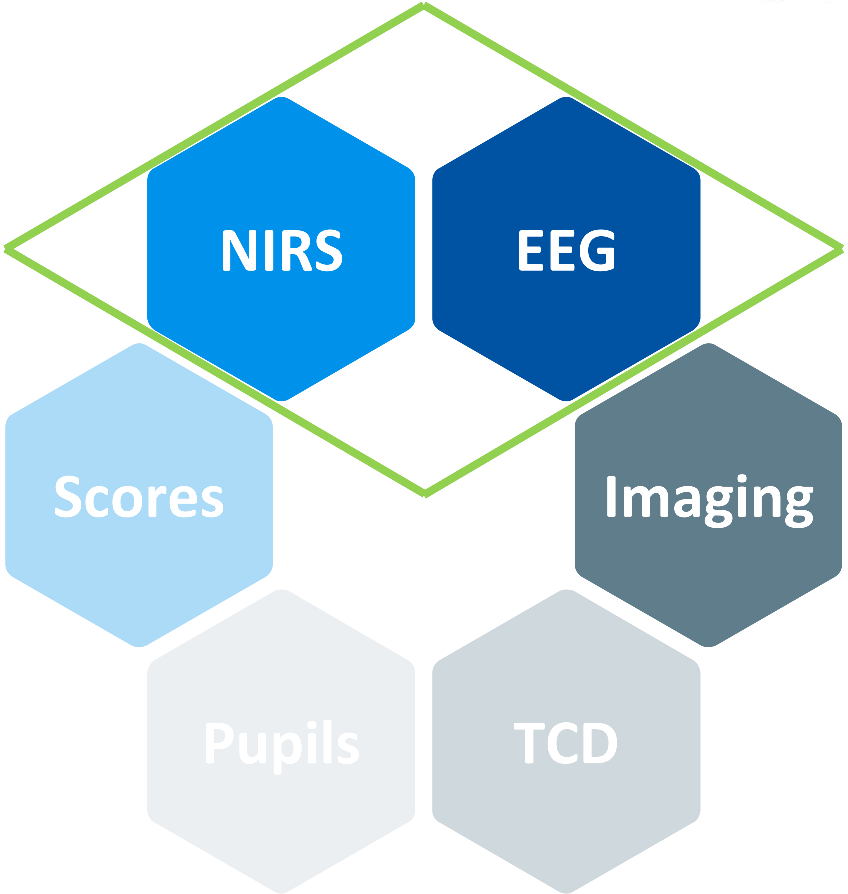
*What does this **mean** for my child?*

Prognostication

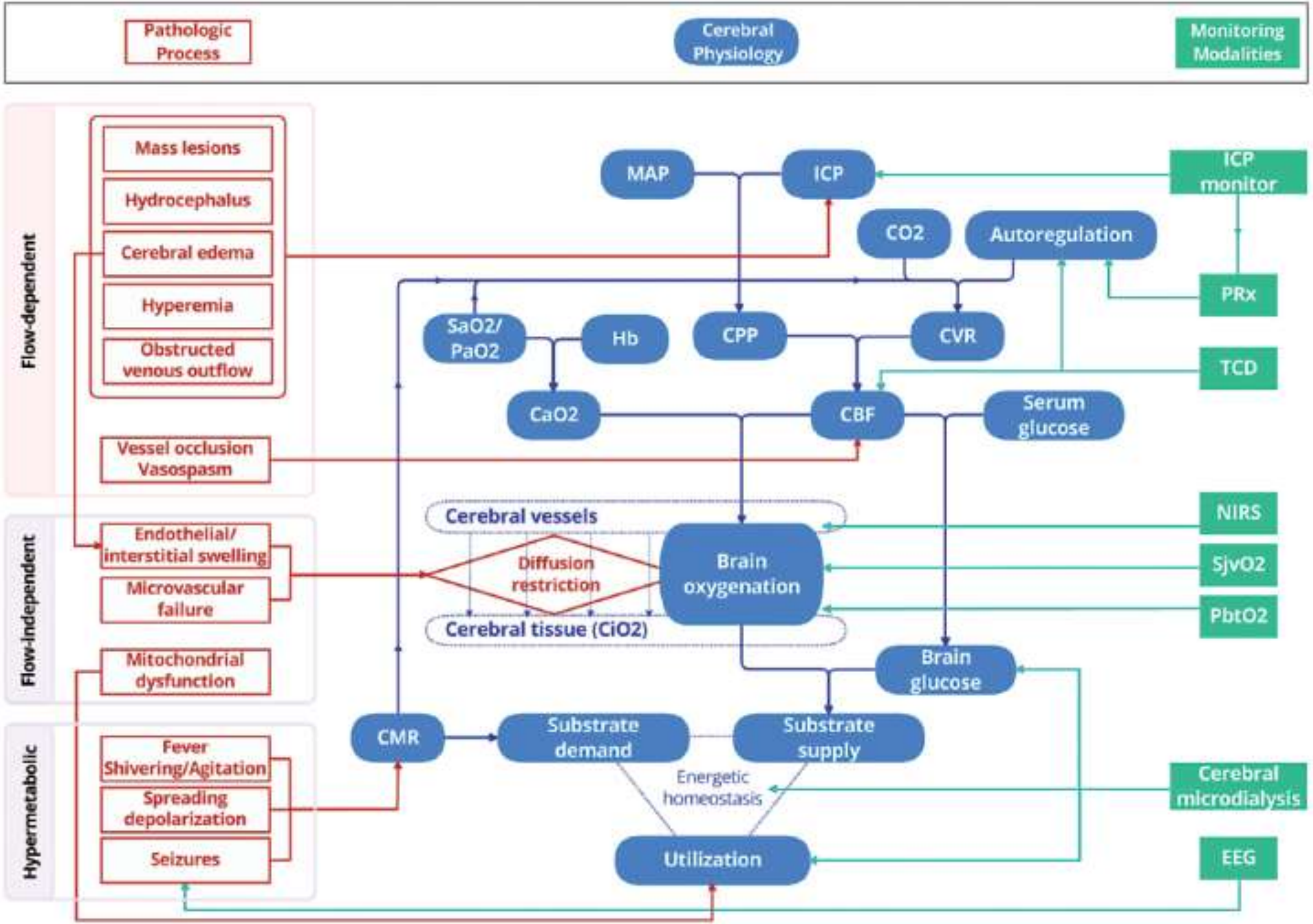


Fischer. Nat Rev Neurol. 2022

Modalities



Brown KL. Intensive Care Med. 2022

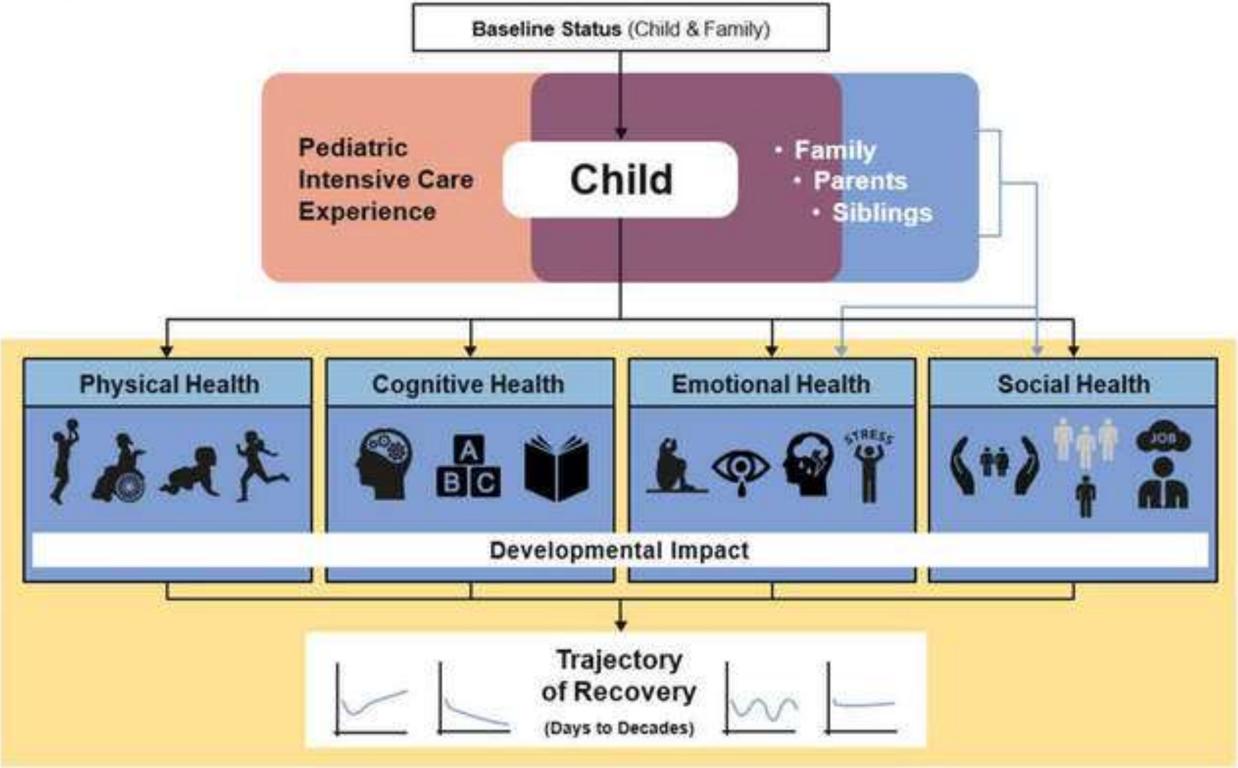


Plante V et al. Semin Neurol. 2024

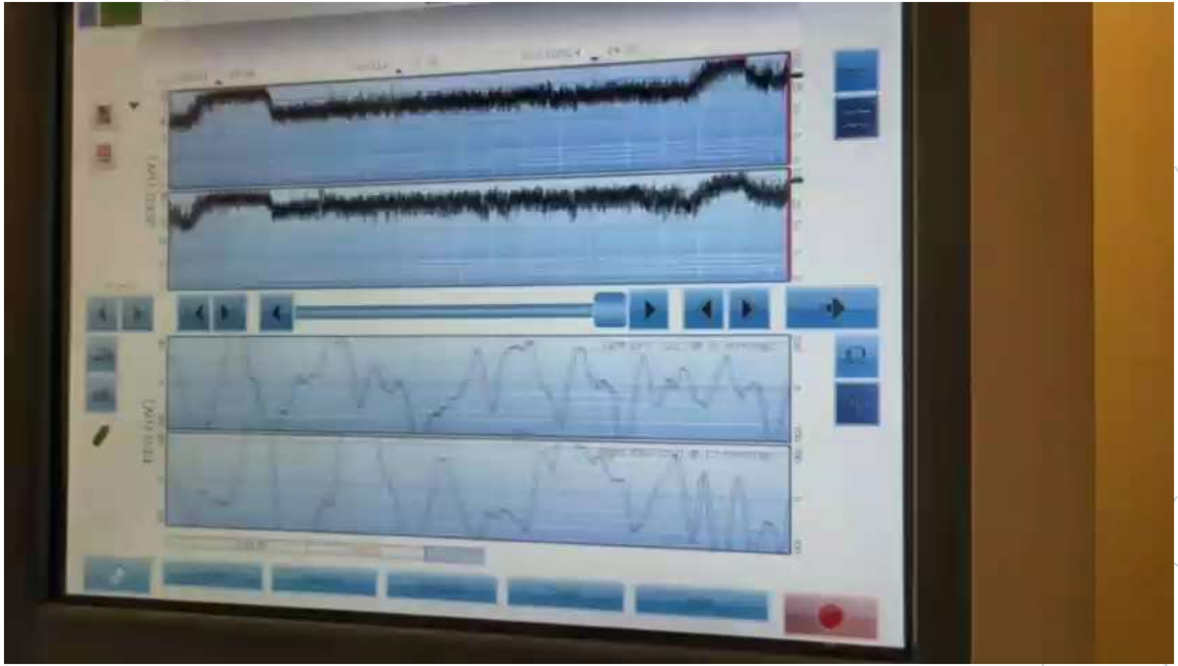
PICS-p

Post-intensive Care Syndrome

Conceptual Framework for Pediatric PICS (PICS-p)



Manning JC, Pinto NP, Rennick JE, Colville G, Curley MAQ. *PCCM* 2018



Electrophysiology

Continuous EEG

Pros: noninvasive, continuous, focal and global assessment

Cons: resource-intensive, retrospective interpretation (diagnosis delay), affected by sedation, prone to artifacts

Detecting electrographic seizures
Monitoring barbiturate coma
Background assessment for cerebral dysfunction

Quantitative EEG

Pros: utilizes existing equipment, brief training, bedside real-time analysis, noninvasive, continuous

Cons: limited pediatric data, lower sensitivity/specificity than cEEG for seizure (requires confirmation with cEEG)

Neonates

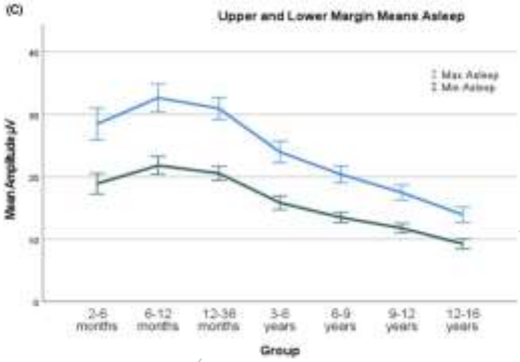
Hirsch ACNS Guideline 2021
Plante Sem Neurol 2024

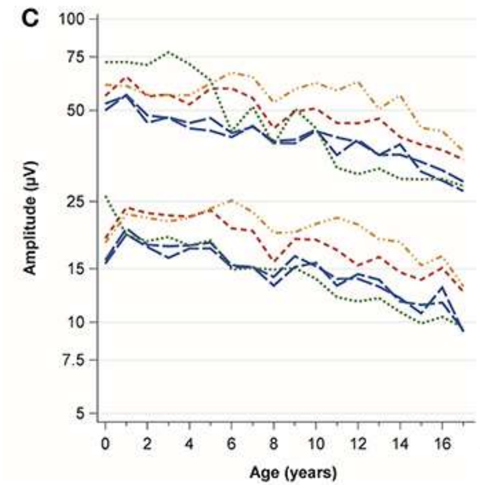
aEEG

Reference Values?

MacDarby ActaPaed 2022

Greve FrontNeurol 2022 – Location!





Role of anesthetics and sedative drugs

- Drug-induced patterns of oscillation -> Visible in raw EEG
- frequency changes hard to discern -> **Spectrogram**

Brandt AnesthAnalg 2020

Multimodal
Neuromonitoring

Combining Systematic and Neurologic Variables

Cases

Neuromonitoring in the Clinical Context

1 in 6

PICU admissions worldwide attributable to acute brain disorder

1.

Resuscitation

Cerebral Oximetry during resuscitation / Benefits

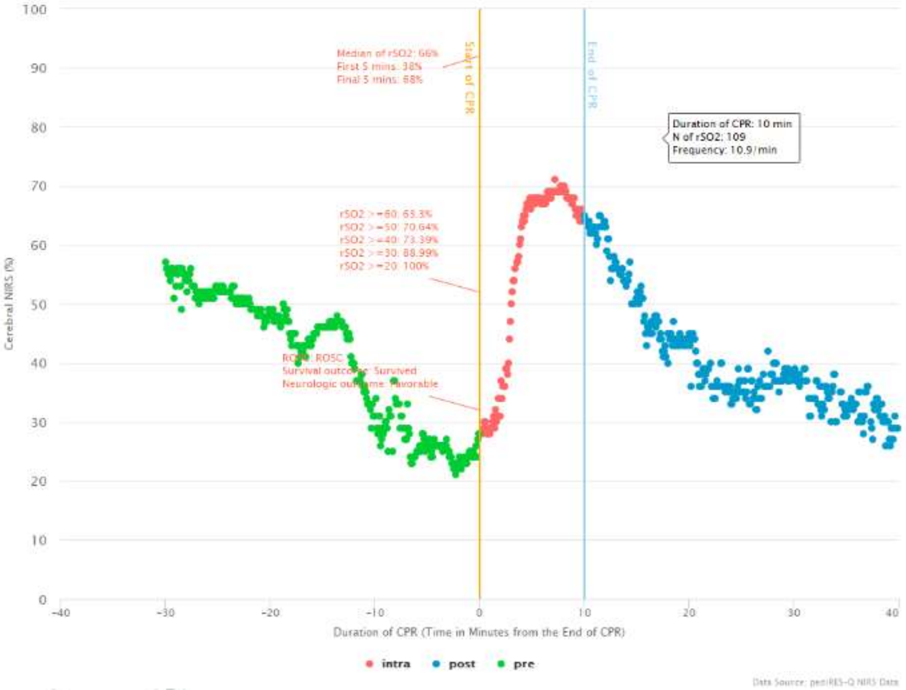
- Already monitored
- Low-flow -> pulse oximetry might not work
- Pathophysiologic rationale
- Adult data [Huppert et al 2022]

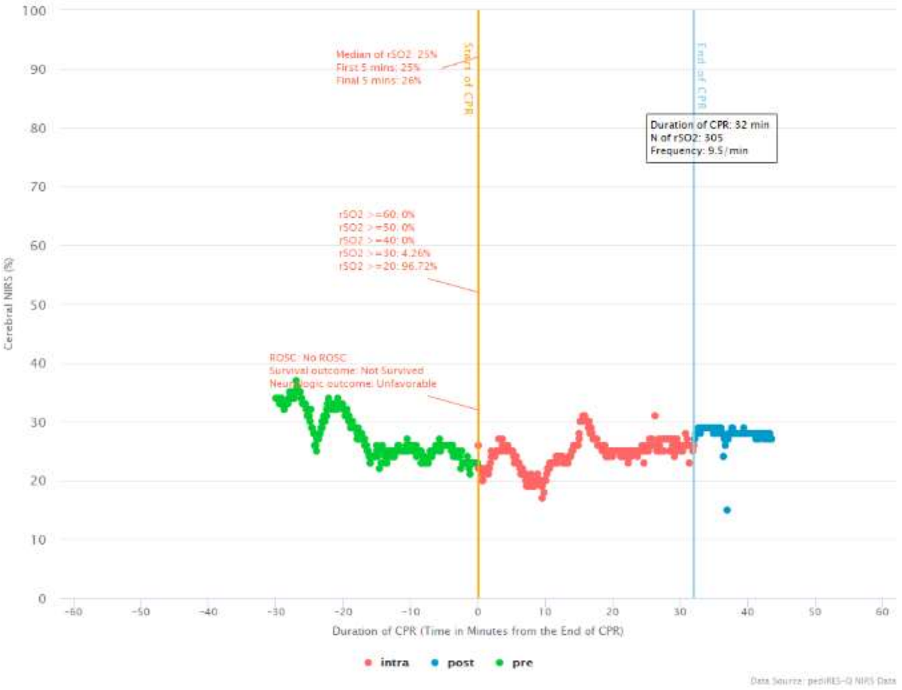
Prospective observational trial / IHCA

- Higher rSO2 ➔ higher ROSC
- Cutoffs? Esp. Epochs above 50%
- ➔ no higher survival to d/c

Francoeur C. Resuscitation. 2022

Prospective observational trial / IHCA / PediRes-Q

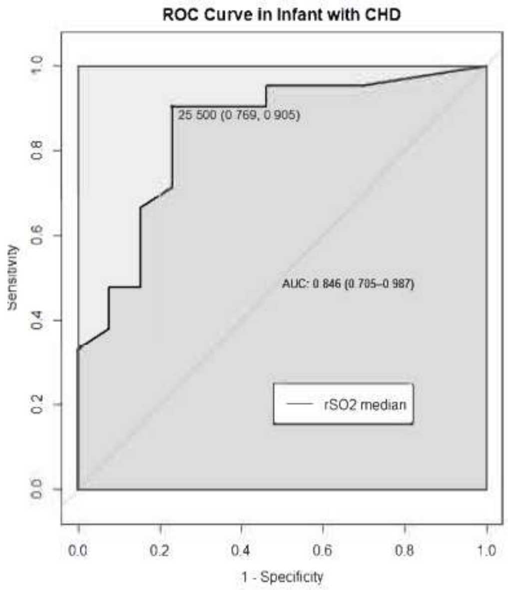




Raymond TT. CCM. 2024

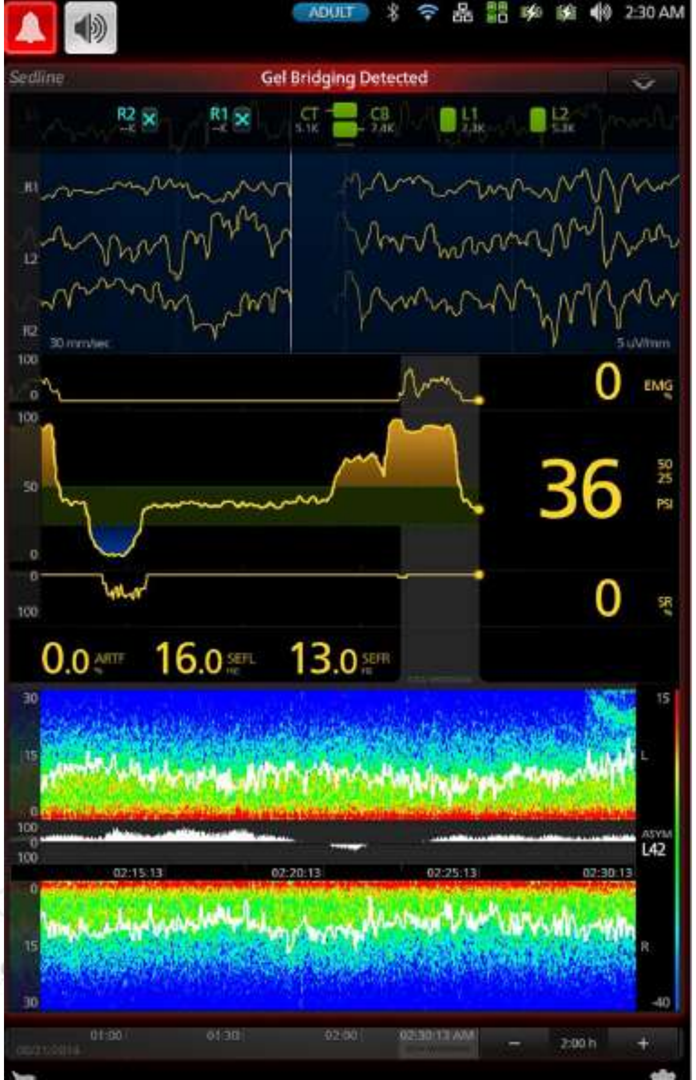
Prospective observational trial / IHCA / PediRes-Q

median crSo2	ROSC	No ROSC
entire CPR event	44% [30–60%]	26% [15–40%]
first 5 minutes	42% [28–58%]	29% [17–42%]
final 5 minutes	44% [32–62%]	30% [16–45%]



- All patients who survived to hospital discharge had a crSo2 above 30% throughout the CPR event

Raymond TT. CCM. 2024



Combining Cerebral Oxygenation and EEG monitoring

Summary

1.

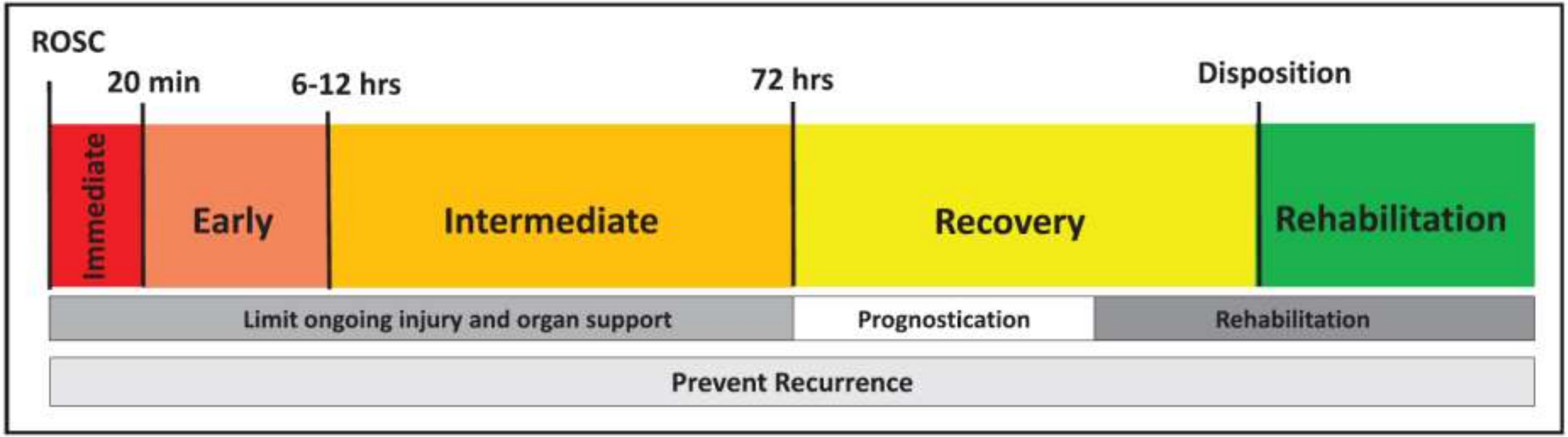
Resuscitation / Cerebral Oxygenation

- Correlates with ROSC
- Single measurement ok
- Cut off point?

2.

Post Resuscitation

Phases during Post-Resuscitation



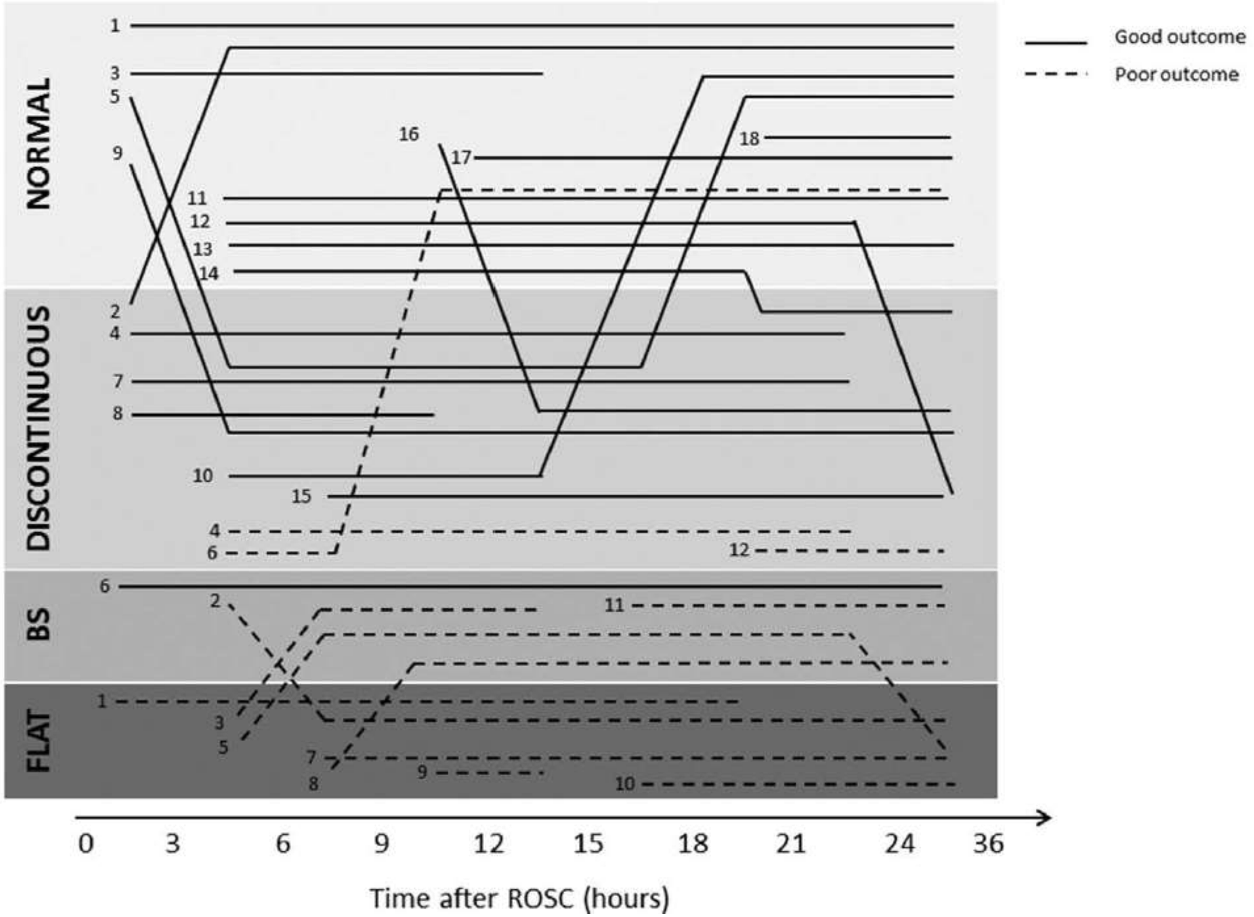
Raymond TT. CCM. 2024

Post-Resuscitation Care

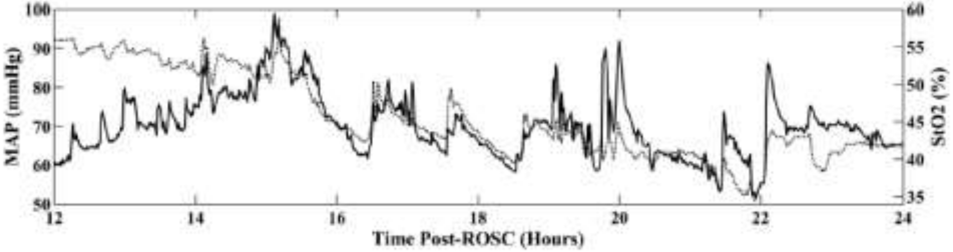
- All children

Children in coma

Using aEEG for prediction after resuscitation



Bourgoin P. Pediatr Crit Care Med. 2020



Cerebral Oxygenation, MAP and cerebral autoregulation

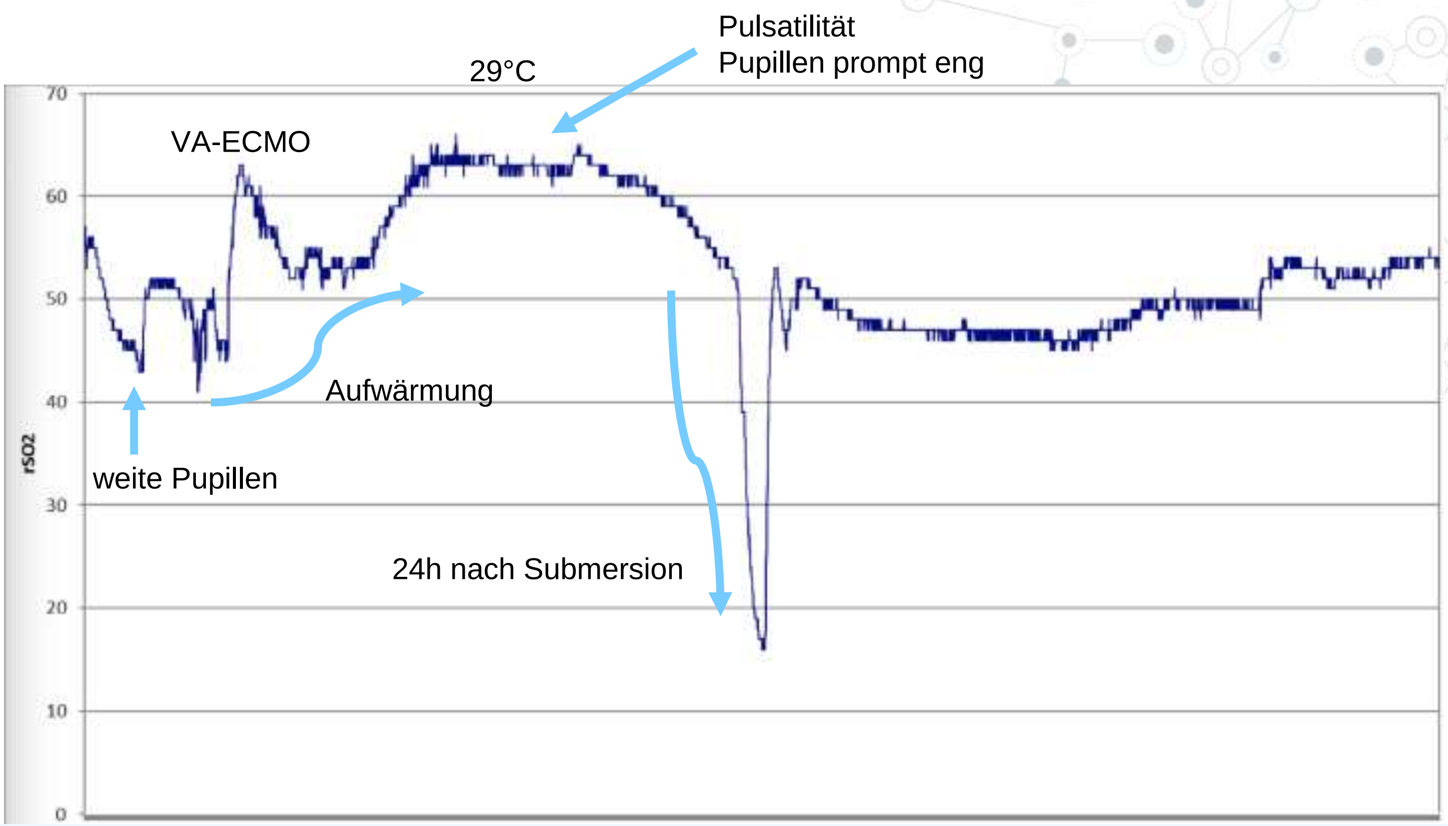
Greater burden of MAP below NIRS-derived MAPopt - 5 during the first 24 h after cardiac arrest was associated with unfavorable
outcomes.

Kirschen Resuscitation 2021

Child 1.5 yr

- 4.30p: „Child is missing“
- Drowning in nearby stream
- 5.15p: child is found (submersion time?)
- 5.35p: CPR -> transport to hospital
  - asystoly, 20-24°C
- 7.30p: arrival in PICU with ongoing CPR
  - Dilated, non-reactive pupils
- ECPR with 24°C: VA-ECMO

NIRS rSO_2



After 48h: TCD: reversed flow, SSEPs negative, dilated, non-reactive pupils

2.

Post-Resuscitation

- Detect seizures
- Role of cerebral oxygenation?
- Prediction?

3.

Cardiac Patient

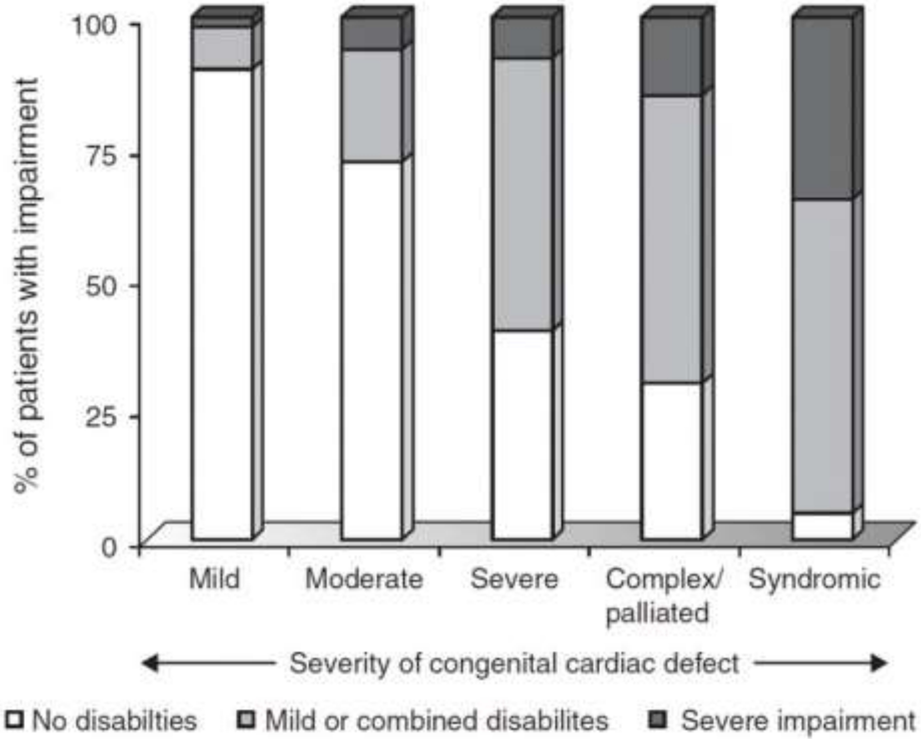
Brain injury common

- White matter injury
- Periventricular leukomalacia
- Stroke

Timing?

Preventable?

Brain injury common in CHD



Marelli Circulation 2017

aEEG for Early Recognition of Brain Injury in Neonates with Critical CHD

- Abnormal BGP 24%
- Ictal discharges 17%

→ **Abnormal brain activity OR 4.0**
For new postoperative brain injury

- majority reached CNV within 24 hours

Claessens JPed 2018

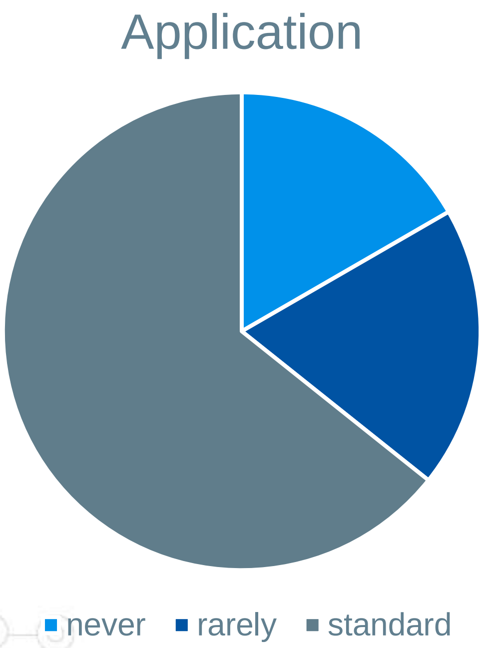
Subclinical seizures common

EEG postoperatively

- 8% electrographic seizures
- Start ~20h after surgery
- 85% only in EEG
- 62% in Status epilepticus

Naim JTCVS 2015

NIRS use in CICU



- 37/42 see benefits in use
- 19/42 would react to a change in NIRS
- Only 4 units had a protocol
- USA: 90% of units used

Hoskote 2016
Rossi 2012

Near-Infrared Spectrometry for Monitoring Patients With Complex Congenital Heart Disease Is Here to Stay*

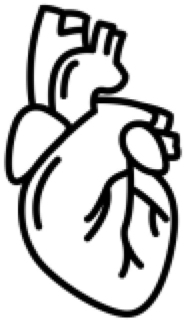
KEY WORDS: congenital heart disease; critical care; near-infrared spectrometry; pediatrics

Anthony F. Rossi, MD
Danyal M. Khan, MD

- Oxygen delivery vs. Oxygen consumption
- NIRS values in children with CHD often lower
- Cerebral Oxygenation Extraction similar (cyanotic vs non-cyanotic)

Editorial PCCM 2023

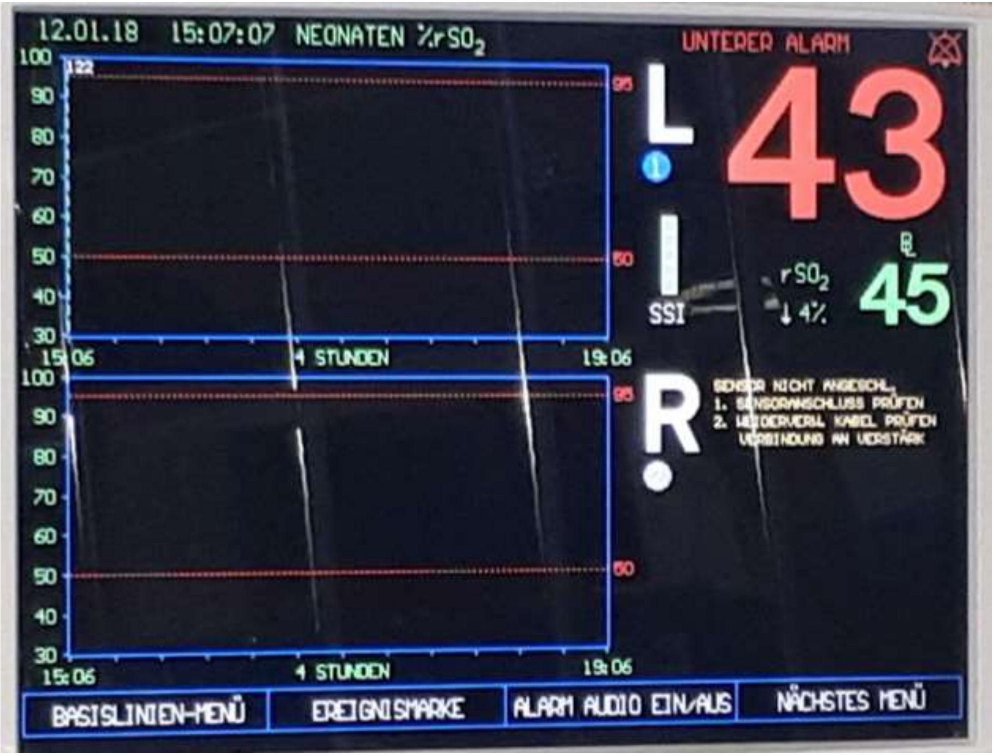
Low cardiac output state (LCOS)



$DO_2 \ll VO_2$

Delivery << Consumption

Early detection → Earlier therapy


12.01.18 15:07:07 NEONATEN %rSO2
UNTERER ALARM
L
43
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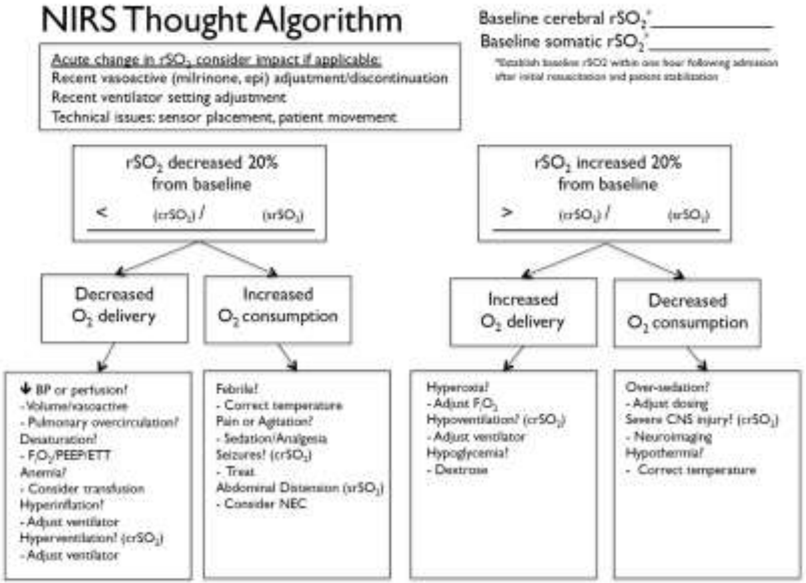
↓ 4%
45
4 STUNDEN
15:06
19:06
NICHT ANGESCHL.
KABEL PRÜFEN
BASISLINIEN-MENÜ
EREIGNISMARKE
ALARM AUDIO EIN/AUS
NÄCHSTES MENÜ

NIRS Algorithm to improve clinical outcomes

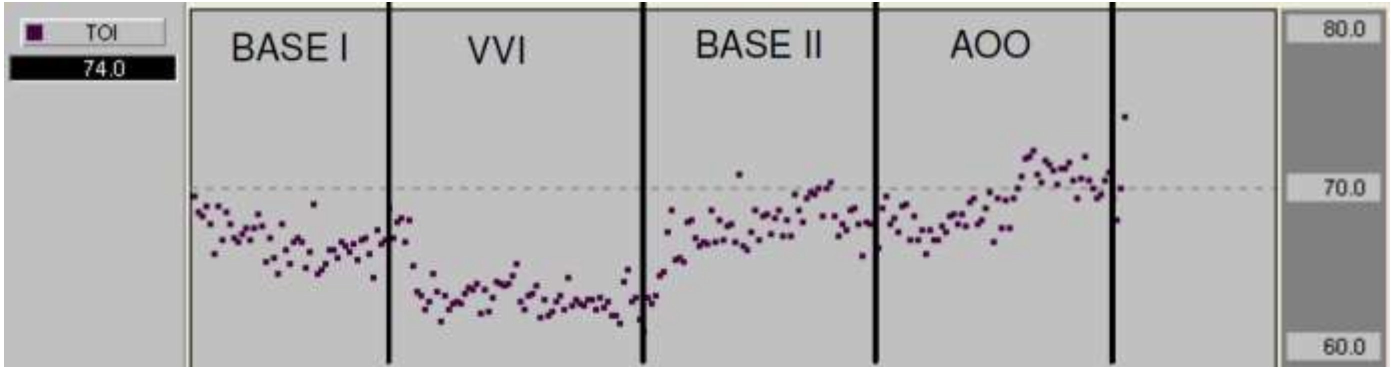


- Before/after study
- Less mortality observed

Watch out for
➔ Decrease of 20%
➔ Values below 30

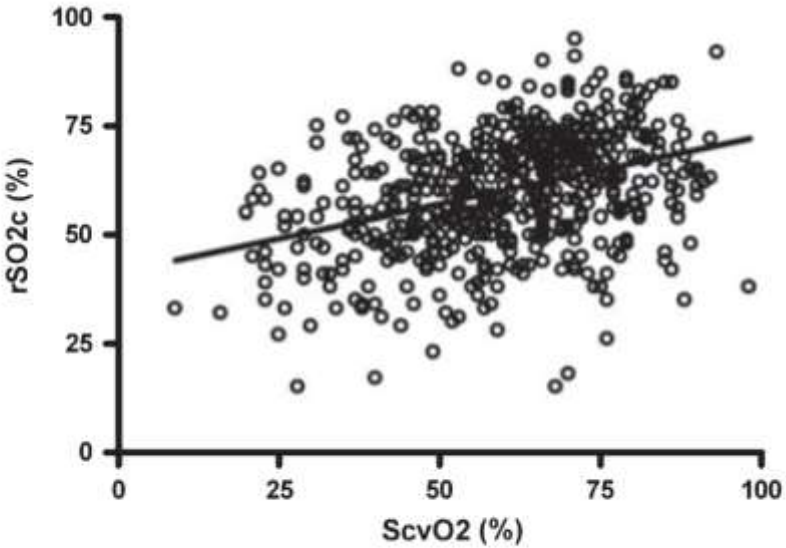
Spaeder 2023

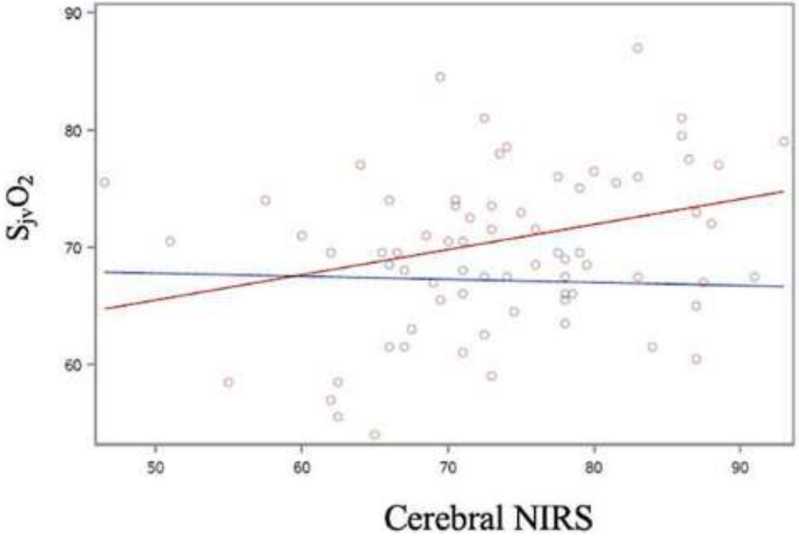
NIRS and cardiac pacing



Fleck 2010

NIRS vs. central venous saturation





Ricci 2010
Iliopoulos 2023

NIRS vs. Lactate

Multisite near-infrared spectroscopy predicts elevated blood lactate level in children after cardiac surgery

- Cerebral rSO(2) had the strongest inverse correlation with lactate level followed by splanchnic, renal, and muscle rSO(2)
- The correlation improved by averaging the cerebral and renal rSO(2) values
- An averaged cerebral and renal rSO(2) value <= 65% predicted a lactate level >or=3.0 mmol/L with a sensitivity of 95% and a specificity of 83%

Chavrati 2009

Prediction of complications of Cardiopulmonary Bypass

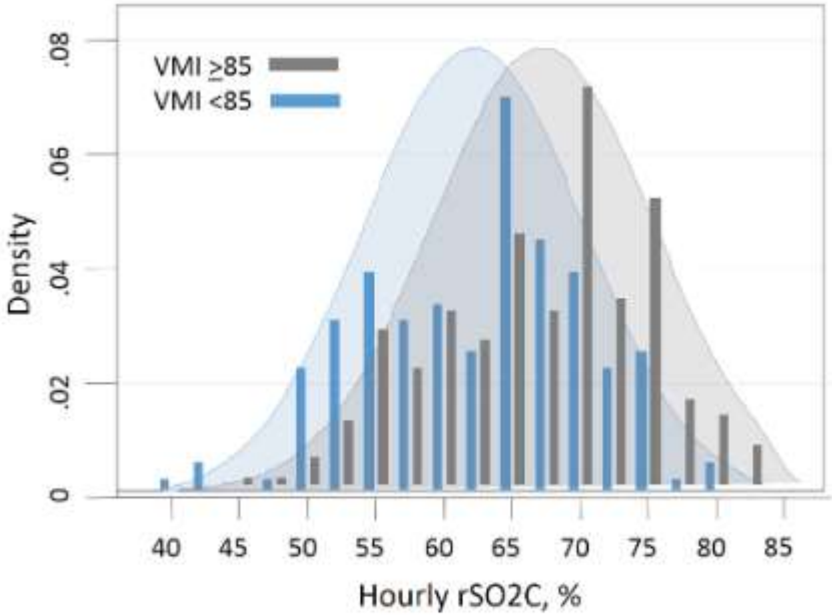
Table 1 Patients' characteristics and intraoperative near-infrared spectroscopy-related values and comparison between patients with major adverse events and patients without major adverse events

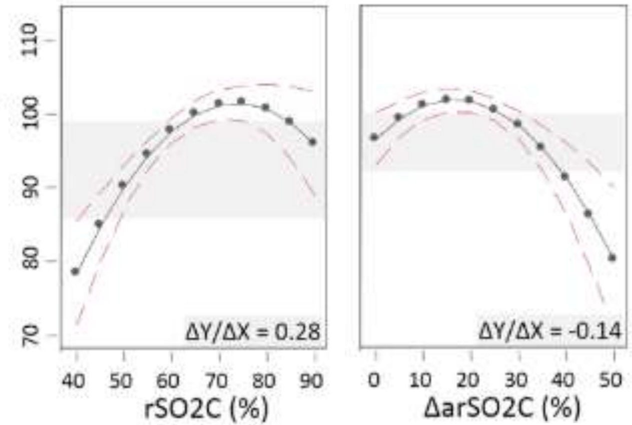
Characteristics	All cases ($n = 647$)	MAE ($n = 16$)	No MAE ($n = 631$)	p-value
Age, month, [IQR]	76.83 [15.00, 187.75]	27.21 [10.25, 52.56]	80.83 [15.00, 189.00]	0.039
Weight, kg [IQR]	4.03 [3.00, 6.06]	3.08 [2.78, 3.63]	4.09 [3.01, 6.13]	0.023
Male, n (%)	376 (58.1)	9 (56.2)	367 (58.2)	1
RACHS-1 [IQR]	3.00 [2.00, 3.00]	3.00 [3.00, 4.00]	3.00 [2.00, 3.00]	0.005
Duration of operation, minute [IQR]	249.00 [200.00, 316.00]	262.50 [248.50, 320.75]	248.00 [199.50, 316.00]	0.316
Duration of cardiopulmonary bypass, minute [IQR]	117.50 [83.00, 165.00]	124.00 [86.50, 174.00]	116.00 [83.00, 165.00]	0.784
Pre-CPB ScO_2, [IQR]	58.74 [53.19, 64.90]	48.60 [40.13, 64.17]	58.89 [53.40, 64.92]	0.01
Pre-CPB variability of ScO_2, [IQR]	1.76 [1.34, 2.66]	2.43 [1.70, 3.22]	1.75 [1.34, 2.64]	0.134
Post-CPB eO_2ER, [IQR]	0.52 [0.44, 0.62]	0.66 [0.60, 0.78]	0.52 [0.43, 0.61]	< 0.001
Post-CPB Lac_{max}, mmol/L [IQR]	2.40 [1.78, 3.90]	2.80 [2.35, 3.45]	2.33 [1.74, 3.95]	0.07

MAE major adverse event, *IQR* interquartile range, *RACHS-1* Risk-Adjusted Classification for Congenital Heart Surgery Version 1, *CPB* cardiopulmonary bypass, ScO_2 regional cerebral oxygen saturation, ScO_2 regional cerebral oxygen saturation, eO_2ER estimated oxygen extraction ratio, Lac_{max} maximum serum lactate level

Kimura 2023

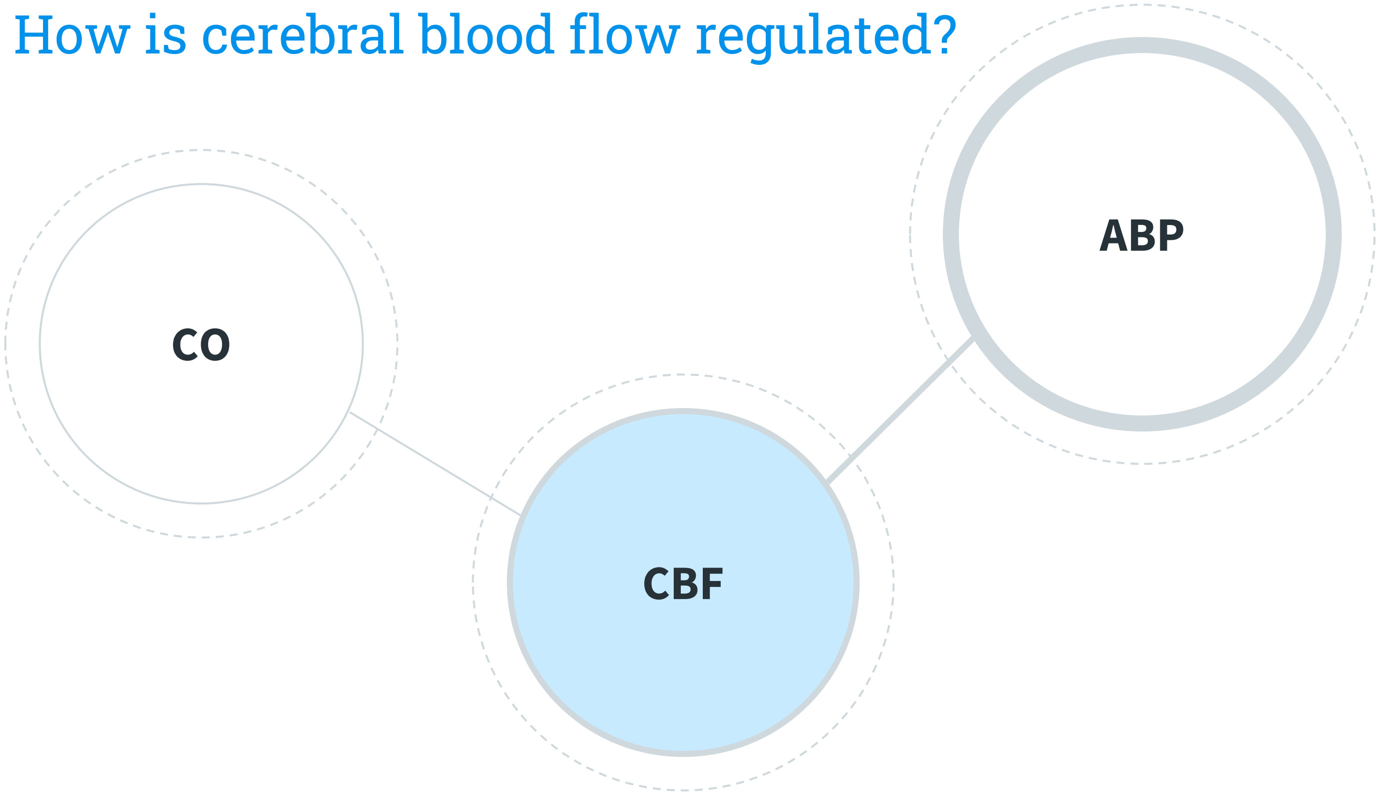
NIRS in CHD and childhood neurodevelopmental outcome





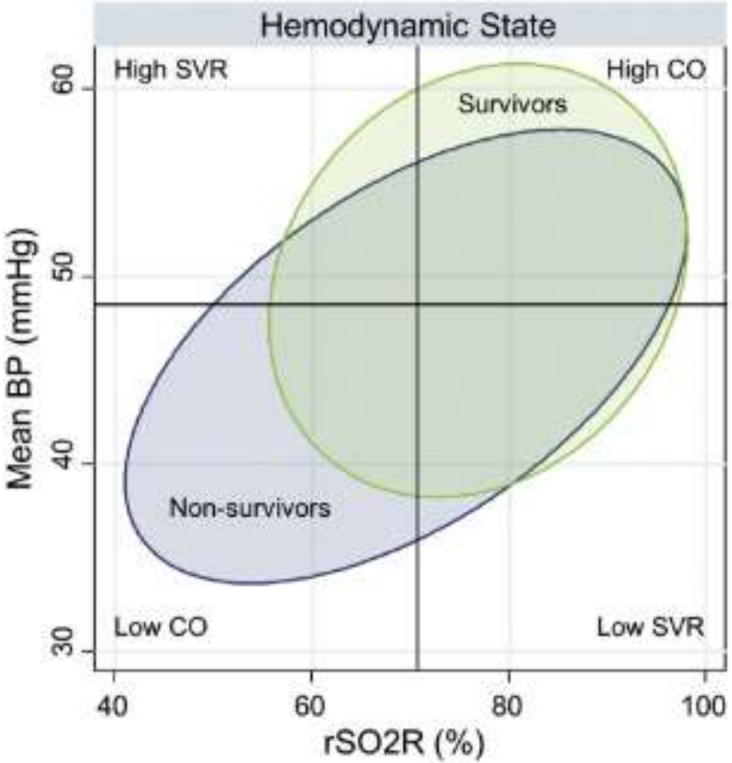
Hoffman JTCVS 2013

How is cerebral blood flow regulated?



Schwartz ATS 1995

Postoperative Cerebral and Somatic NIRS and Outcome in HLHS



Hoffmann ATS 2017

Status Quo – Monitoring Practice

Modality	Pre	Intra	Post-OP
NIRS	64%	80%	72%
aEEG			32%
cEEG			12%
CUS	96%		84%
MRI	72% (*)		44% (*)
Follow-Up			40%

(*) In clinical symptomatic cases

Feldman PedRes 2023

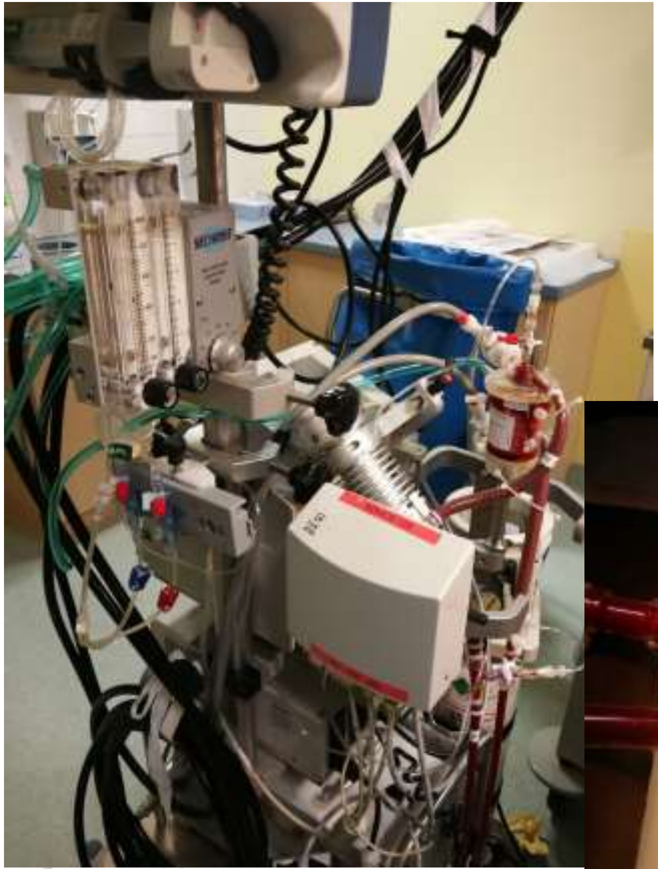
3.

Cardiac Patients

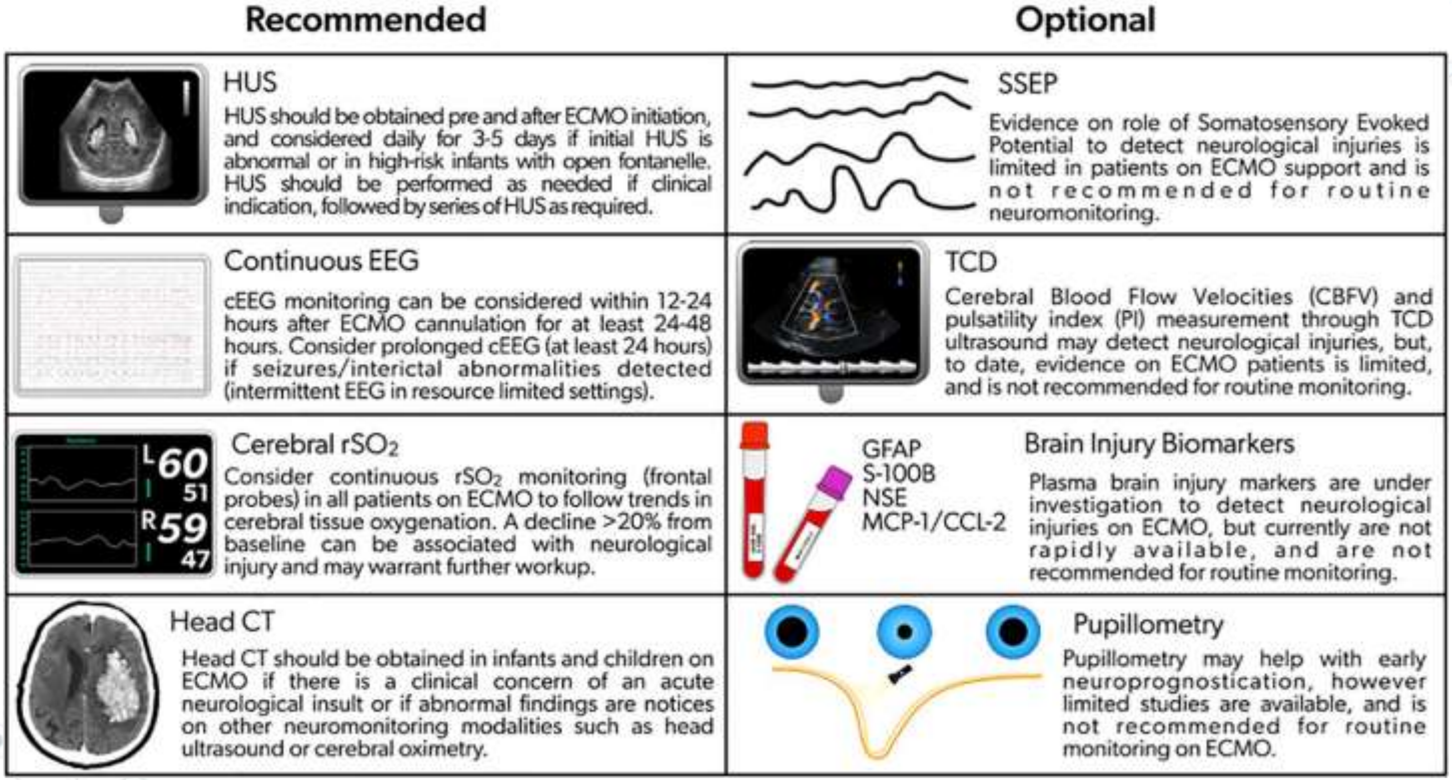
- Emerging
- Seizure detection
- Ideal Blood pressure? DO_2 vs. VO_2?
- Prediction?

4.

Patient on ECMO



ELSO Recommendations for Neuromonitoring on ECMO



Recommended	Optional
HUS HUS should be obtained pre and after ECMO initiation, and considered daily for 3-5 days if initial HUS is abnormal or in high-risk infants with open fontanelle. HUS should be performed as needed if clinical indication, followed by series of HUS as required.	**SSEP** Evidence on role of Somatosensory Evoked Potential to detect neurological injuries is limited in patients on ECMO support and is not recommended for routine neuromonitoring.
Continuous EEG cEEG monitoring can be considered within 12-24 hours after ECMO cannulation for at least 24-48 hours. Consider prolonged cEEG (at least 24 hours) if seizures/interictal abnormalities detected (intermittent EEG in resource limited settings).	**TCD** Cerebral Blood Flow Velocities (CBFV) and pulsatility index (PI) measurement through TCD ultrasound may detect neurological injuries, but, to date, evidence on ECMO patients is limited, and is not recommended for routine monitoring.
Cerebral rSO_2 (L 60 / 51, R 59 / 47) Consider continuous rSO_2 monitoring (frontal probes) in all patients on ECMO to follow trends in cerebral tissue oxygenation. A decline >20% from baseline can be associated with neurological injury and may warrant further workup.	**Brain Injury Biomarkers** (GFAP, S-100B, NSE, MCP-1/CCL-2) Plasma brain injury markers are under investigation to detect neurological injuries on ECMO, but currently are not rapidly available, and are not recommended for routine monitoring.
Head CT Head CT should be obtained in infants and children on ECMO if there is a clinical concern of an acute neurological insult or if abnormal findings are notices on other neuromonitoring modalities such as head ultrasound or cerebral oximetry.	**Pupillometry** Pupillometry may help with early neuroprognostication, however limited studies are available, and is not recommended for routine monitoring on ECMO.

Pandiyan P. ASAIO J. 2023

Neuromonitoring on ECMO

Modality	Total	Pediatric Centers
Intermittent EEG	39%	35%
Continuous EEG	14%	10%
aEEG	17%	48%
Cranial Ultrasound	37%	73%
Transcranial Doppler	29%	28%
NIRS	66%	80%
Evoked potentials	15%	8%
Plasma biomarkers	25%	8%
Carotid Doppler	6%	3%
Routine Neuroimaging	54%	77%

Cvetkovic Perfusion 2021

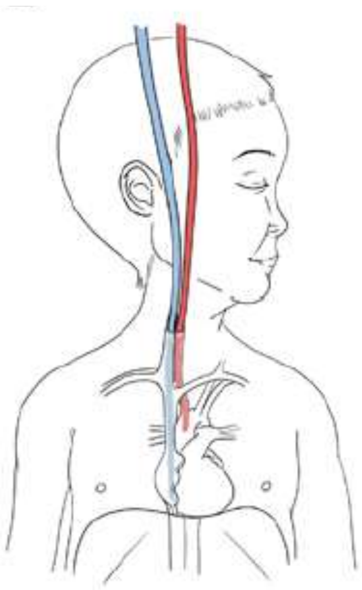
Acute desaturation on ECMO association with poor outcome

Any cerebral desaturation	aOR 4
Any rScO2 decline > 20% from baseline	aOR 3.9
Mean rScO2 < 70%	aOR 5.6
Diagnostic performance as predictors	**poor**

Vedrenne-Cloquet M. Neurocrit Care. 2021

Prognostication on ECMO with NIRS

- 34 infants < 3 Mo
- Mortality 50%, Brain Injury 20%
- NIRS-Values
  - Survivors vs Non-survivors
  - R: 69 vs 54 L: 67 vs 52



Clair PlosOne 2017

Electroencephalography with ECMO

- Continuous EEG monitoring first 24-48h
- Seizure detection – 18-23% of children
  - 56-83% subclinical seizures
  - 30-50% status epilepticus
  - => assoc with poor outcome

4.

ECMO Patients

- Established
- Seizure detection
- Acute problems
- Prediction?

5.

Post-Traumatic Patient

Let’s start with the first set of slides

Traumatic Brain injury / TBI

Wide range of modalities

- automated pupillometry
- optic nerve sheath diameter
- NIRS
- transcranial Doppler
- cEEG
- **Intracranial pressure (ICP)**
- PbtO2 (regional brain tissue oxygen tension)
- cerebral microdialysis
- intracranial EEG
- laser doppler flowmetry
- thermal diffusion flowmetry

Agrawal Neurocrit Care 2023

Neuromonitoring

cEEG	Seizures, Background Electrical activity	Noninvasive, continuous Quantitative and qualitative assessment Can help with prognosis, depth of encephalopathy	Resource intensive Sedation can affect interpretation
Near-Infrared spectroscopy	Regional cerebral oxygenation	Noninvasive CA indices	Poor correlation in presence of hematoma/bleeding Limited spatial resolution Interference from extracranial tissue

Agrawal Neurocrit Care 2023

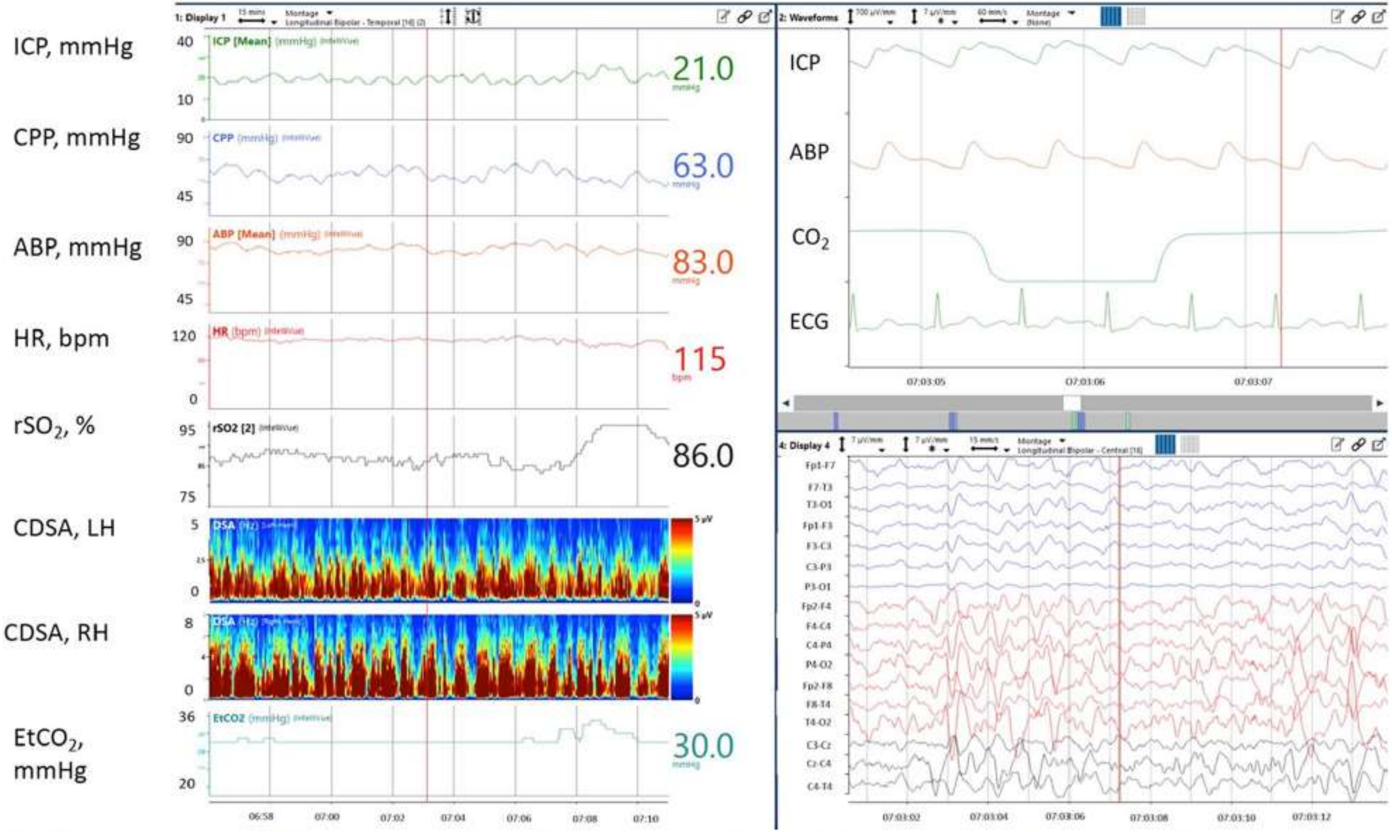


Fig. 1 A 13-year-old female patient with traumatic brain injury undergoes multimodality neurologic monitoring. Increases in ICP are associated with periodic bursts of delta activity, maximal over the right hemisphere. Subsequent neuroimaging demonstrates worsened left hemispheric cerebral edema with midline shift, and the patient undergoes a left hemispheric decompressive craniectomy. *ABP* arterial blood pressure, CO_2 carbon dioxide, *CPP* cerebral perfusion pressure, *CSDA* color dense spectral array, *ECG* electrocardiogram, $ETCO_2$ end-tidal carbon dioxide, *HR* heart rate, *ICP* intracranial pressure, *LH* left hemisphere, *RH* right hemisphere, rSO_2 cerebral regional oximetry. Credit to Brian Appavu, MD

Considerations for implementation of a pediatric multi-modal neuromonitoring program

- Identify key stakeholders
- Identify system to be used (kiosk vs. distributed)
- Identify planned monitoring devices and ensure compatibility with multi-modal neuromonitoring system.
- Determine mechanism for data transfer, data storage, and interface with EMR
- Identify patient populations to be monitored
- Identify method for bedside and remote review
- Identify composition of multi-modal neuromonitoring clinical team
- Determine process for multi-disciplinary review and discussion of data
- Determine standardized process for reporting/documentation of results of multimodal monitoring
- Develop patient care/management protocols for multimodal neuromonitoring
- Create process for equipment care, setup, and connection when patient identified
- Create process for cleaning and preparation of multimodal system for next patient if kiosk monitor is used
- Determine plan for education of nurses and bedside clinicians

5.

Post-traumatic

- ICP - Standard of care
- Seizure detection
- NIRS: additional value?

Summary

	cEEG	aEEG	NIRS
Resuscitation			Research
Post-Resus	Established	Established	Emerging clinical
Cardiac Surgical	Emerging clinical	Emerging clinical	Emerging clinical
ECMO	Established	Established	Established
Post-Trauma	Established	Established	Emerging clinical

Seizure detection

Established (green) | Emerging clinical (blue) | Research (orange)

Plante SemNeurol 2024

Summary 2

◎ Electrophysiology

cEEG	Pros: noninvasive, continuous, focal and global assessment Cons: resource-intensive, retrospective interpretation (diagnosis delay), affected by sedation, prone to artifacts	ACNS 2021 guidelines for recording and reporting should be used[154]
qEEG	Pros: utilizes existing equipment, brief training, bedside real-time analysis, noninvasive, continuous Cons: limited pediatric data, lower sensitivity/specificity than cEEG for seizure (requires confirmation with cEEG)	Amplitude EEG (aEEG) Suppression ratio Alpha–delta ratio Asymmetry index

◎ NIRS

NIRS	Pro: noninvasive, continuous, easy and quick to use, small and portable Cons: interference from noncerebral tissue (scalp edema, skin pigmentation, hematomas, light), low spatial resolution (frontal region), proprietary algorithms	Decline >20% from baseline $crSO_2$ <50%[165,166] Left-to-right asymmetry >10% No absolute normal values Trends are more useful

Plante SemNeurol 2024


I MUST SAY, THE FUTURE IS QUITE A BIT DIFFERENT THAN I EXPECTED.

Thanks!

Any questions?

You can find me at:

@fracardo.bsky.social &
francesco.cardona@muv.ac.at