Neuromonitoring au cours de la chirurgie cardiaque pédiatrique sous CEC.

Pierre BOURGOIN, Anesthésiste Réanimateur,

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Fédération Cardiologie Pédiatrique et Congénitale

Nantes, France

Actualisation 09/01/2026: DIU Anesthésie Réanimation des Cardiopathies Congénitales

Plan

- Introduction: conséquences neurologiques de la CEC
- Débit Sanguin cérébral, estimation par la NIRS
- Autorégulation cérébrale pendant la CEC
  - Théorie
  - Mesure non invasive, Cox
  - Résultats préliminaires en pédiatrie
- Autres éléments du neuromonitoring per CEC
- Conclusion

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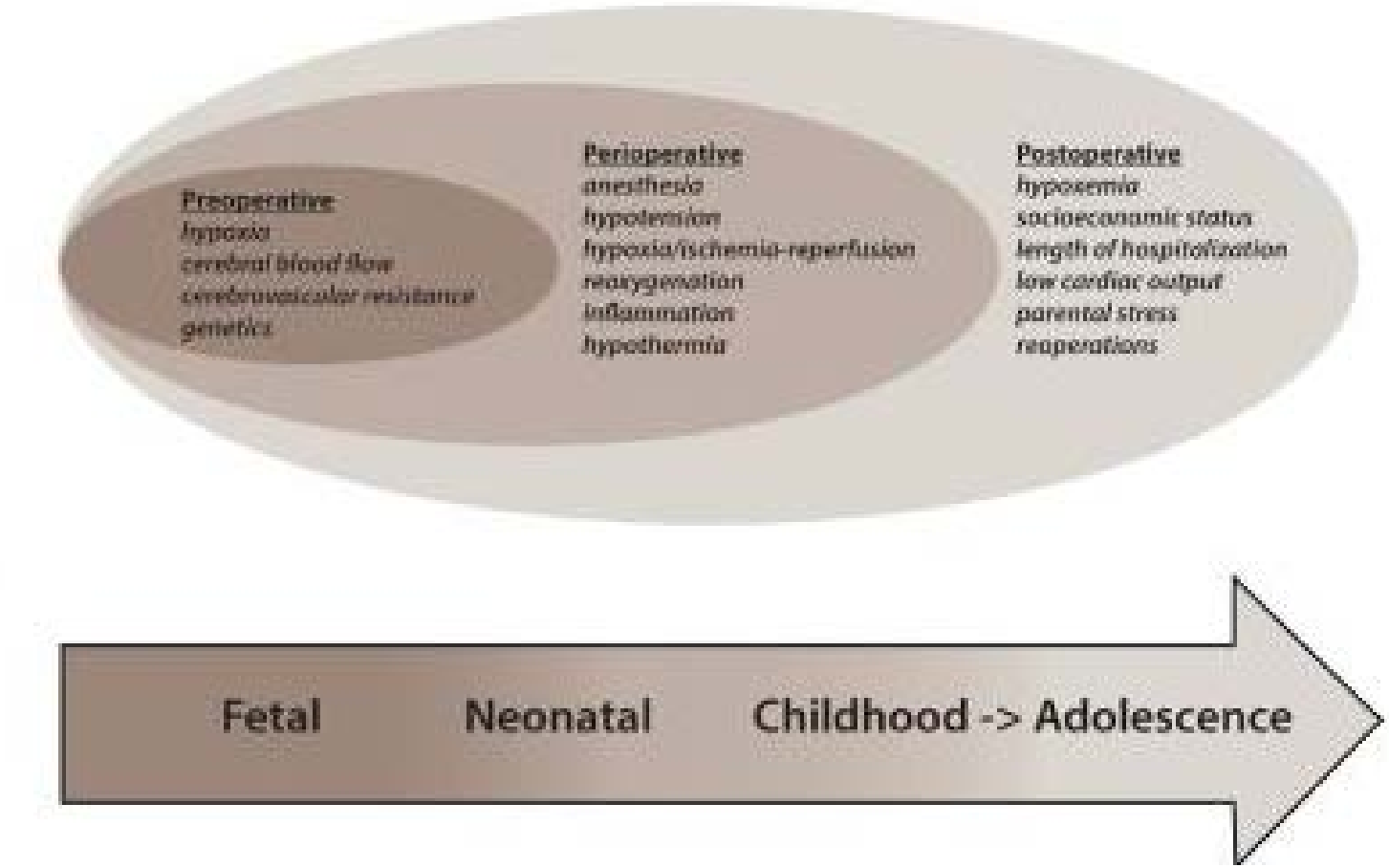
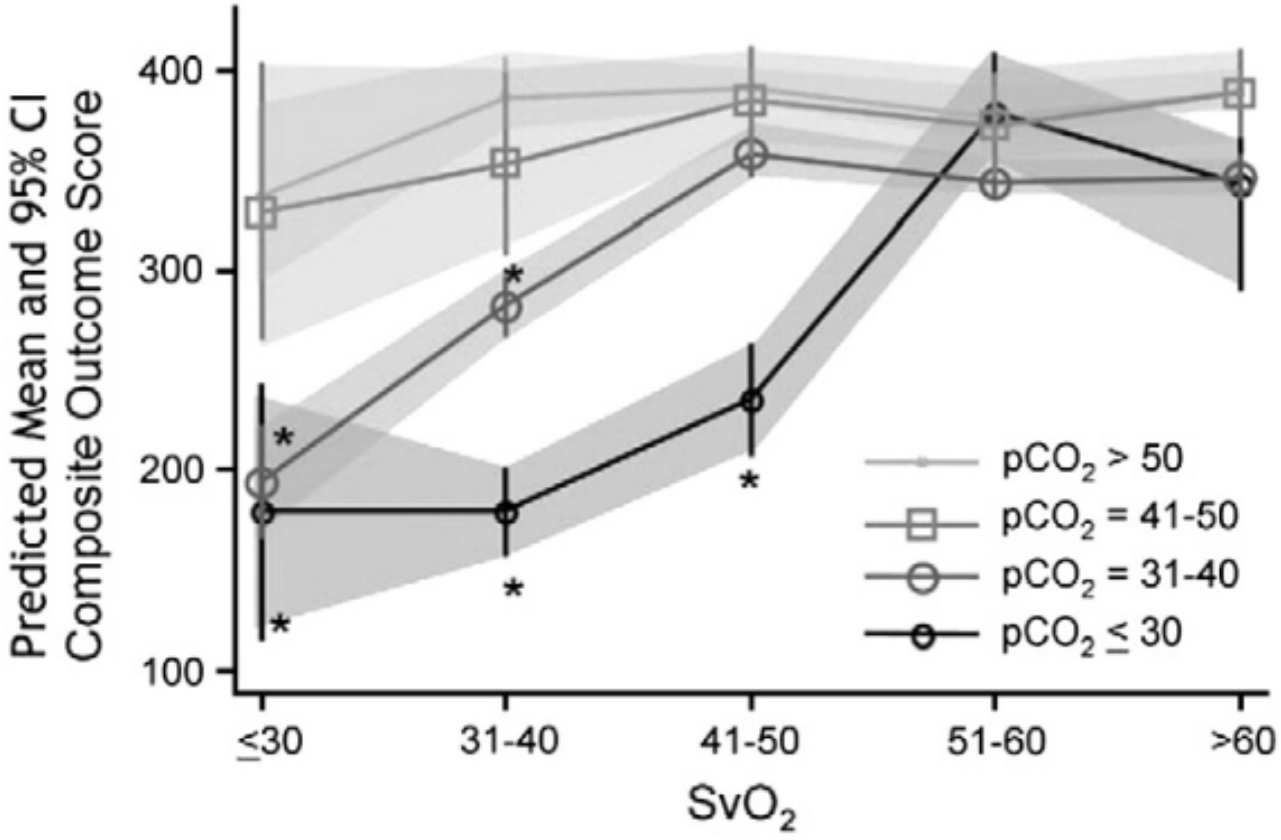
Neurodevelopmental outcomes in children w/ CHD



Does the anesthesiologist play any role?

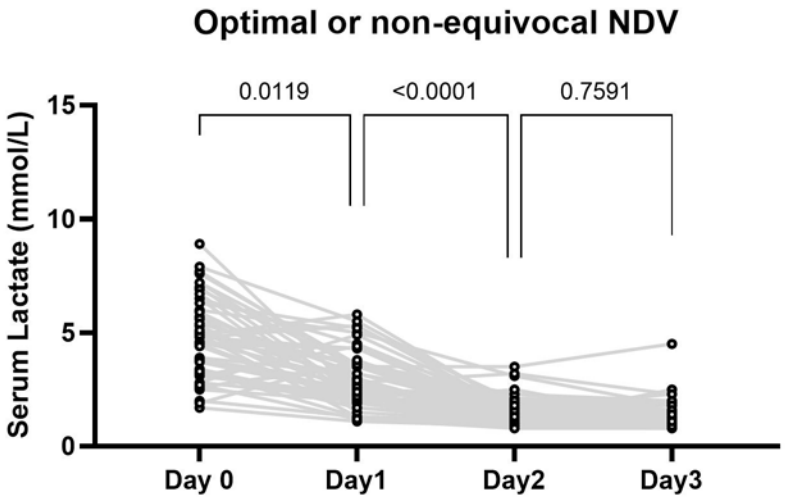


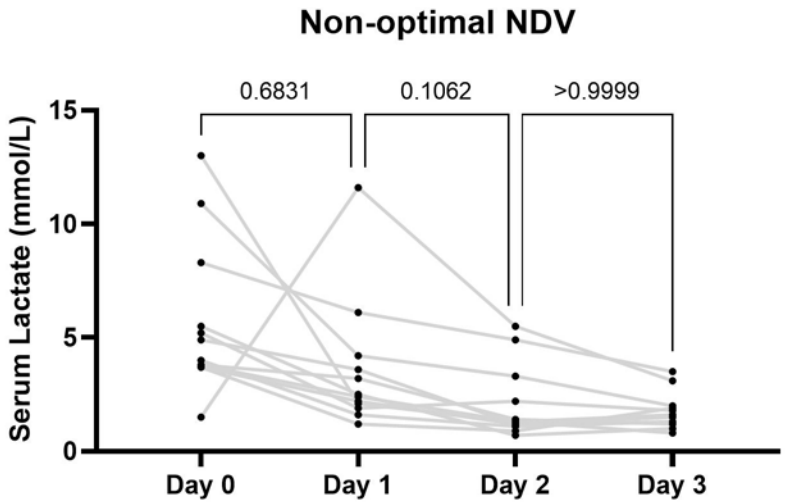
Hoffman GM *Anesthesiology* 1997

> TND après chirurgie cardiaque néonatale

Perioperative Factors Associated with 2-Year Neurodevelopmental Outcome in Neonates Undergo Surgery with Cardi Single-Center Coh

Research | Published: 31 May 2025





Specific domain				
Communication	69	43±16	36.5	20 (29.8%)
Global motor	69	49±13	36	8 (11.8%)
Fine motor	69	51±10	36.4	6 (8.7%)
Problem solving	69	47±10	32.9	12 (17.4%)
Personal-social	69	46±11	35.6	16 (23.2%)
ASQ-total	69	238±47		

Mycinski et al, 2025

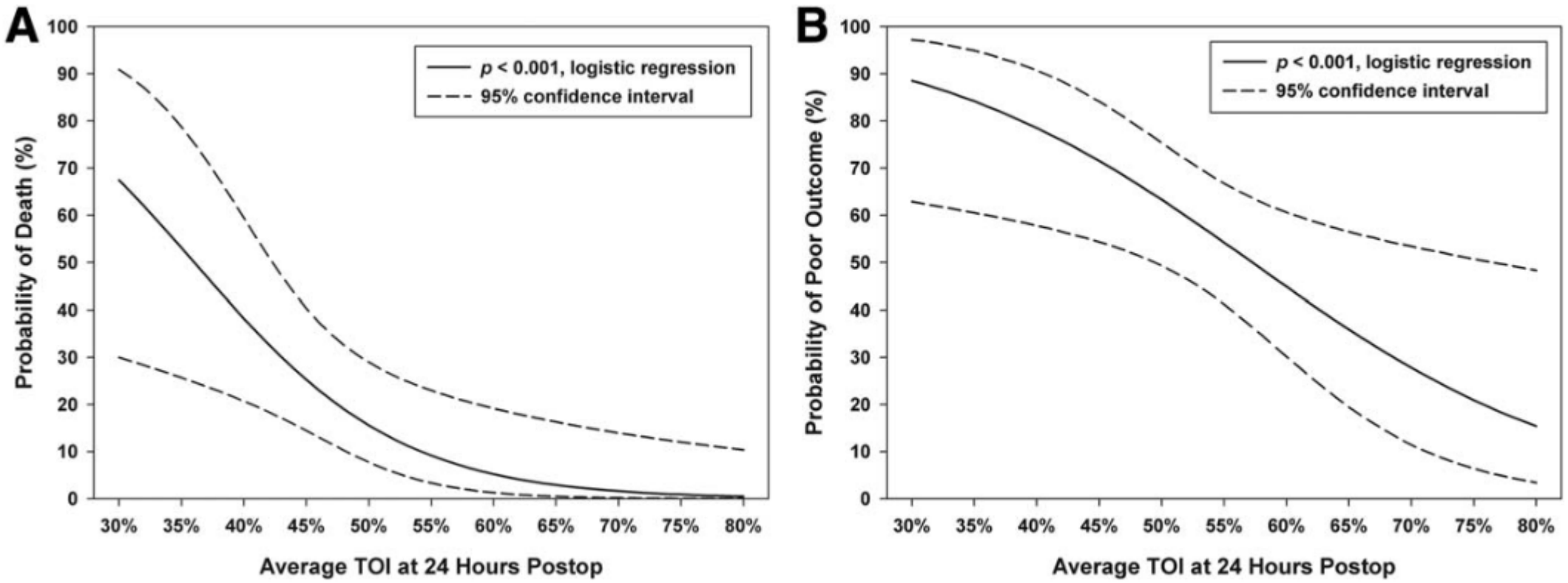
ORIGINAL ARTICLE

WILEY Congenital Heart Disease

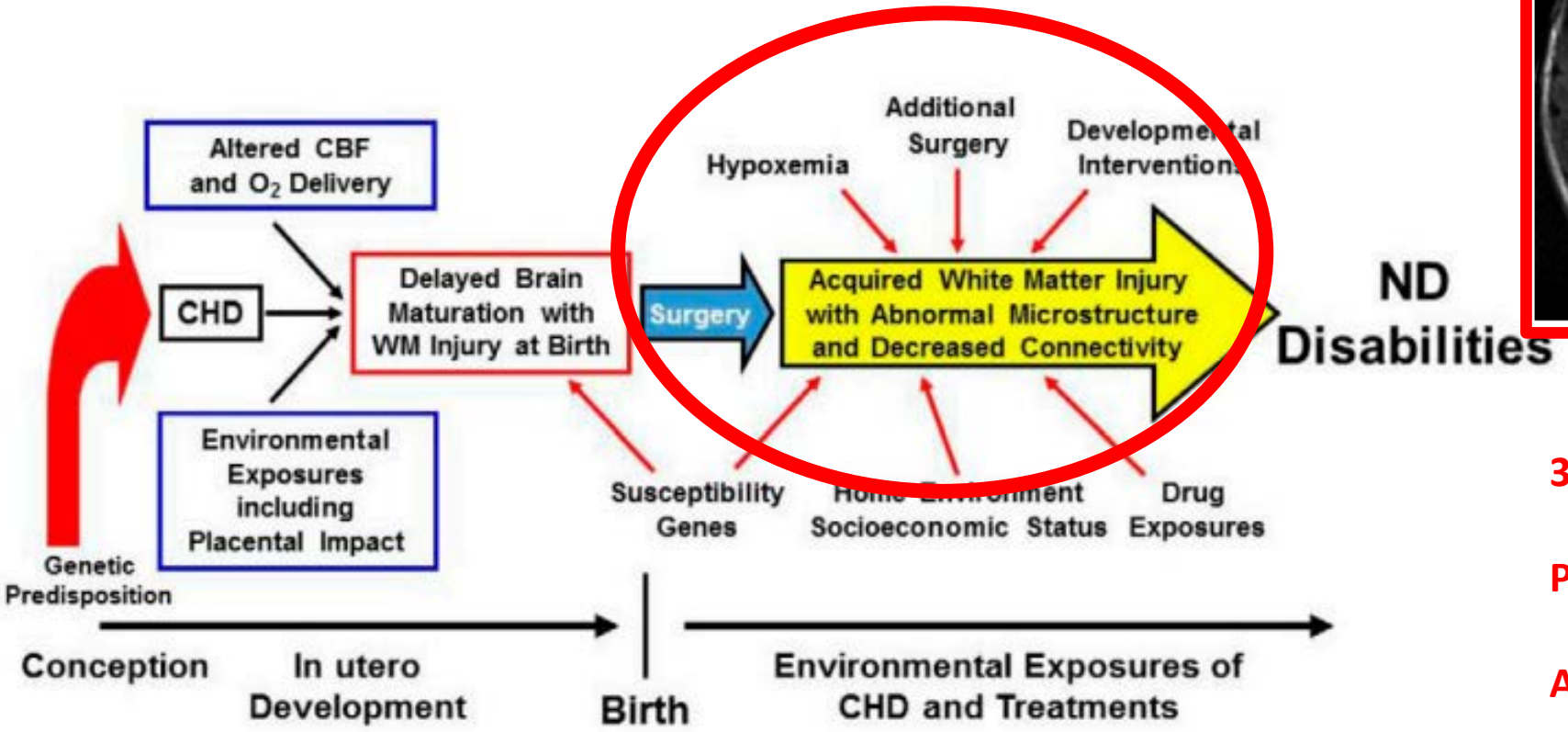
2017

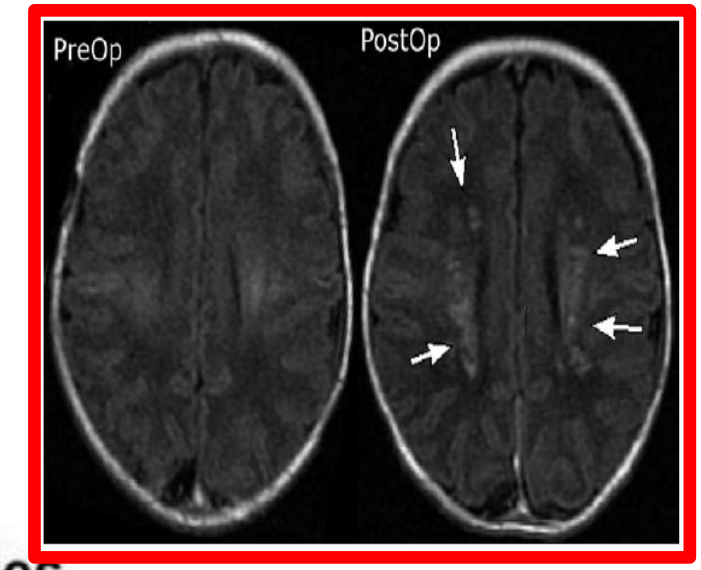
Cerebral tissue oxygenation index and lactate at 24 hours postoperative predict survival and neurodevelopmental outcome after neonatal cardiac surgery

Safwat A. Aly, MD, MSc[1] | David Zurakowski, PhD[2] | Penny Glass, PhD[3] | Kami Skurow-Todd, MSN[4] | Richard A. Jonas, MD[5] | Mary T. Donofrio, MD[4]



Optimizing Neurodevelopmental Outcomes in neonates and children with Congenital heart diseases





30-50% New diagnosed WMI

Perioperative Hypoxia

Abrupt changes in CBF

Ortineau C Peds 2022

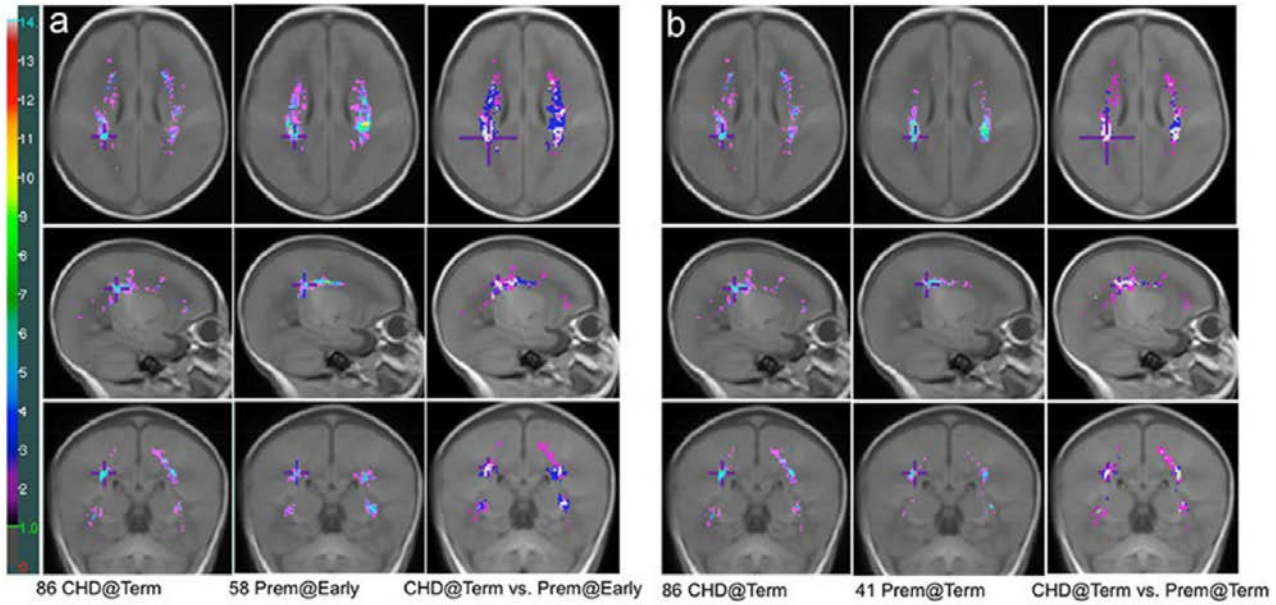
MRI assessment of Neurologic injury after CHD Surgery

Microembols, Bleeds:

→ Fréquents,
→ Quantifiables (MRI injury Score)
→ Association pronostique?

Lésions périventriculaires:

→ Nouveau-né,
→ Analogie preterm
→ Liés aux modifications de CBF
→ Immaturité BBB
→ WMInjury
→ Association pronostique possible



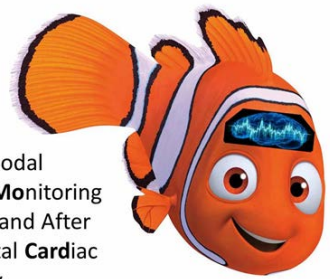
Guo et Al, Neuroimage 2019

Stroke:

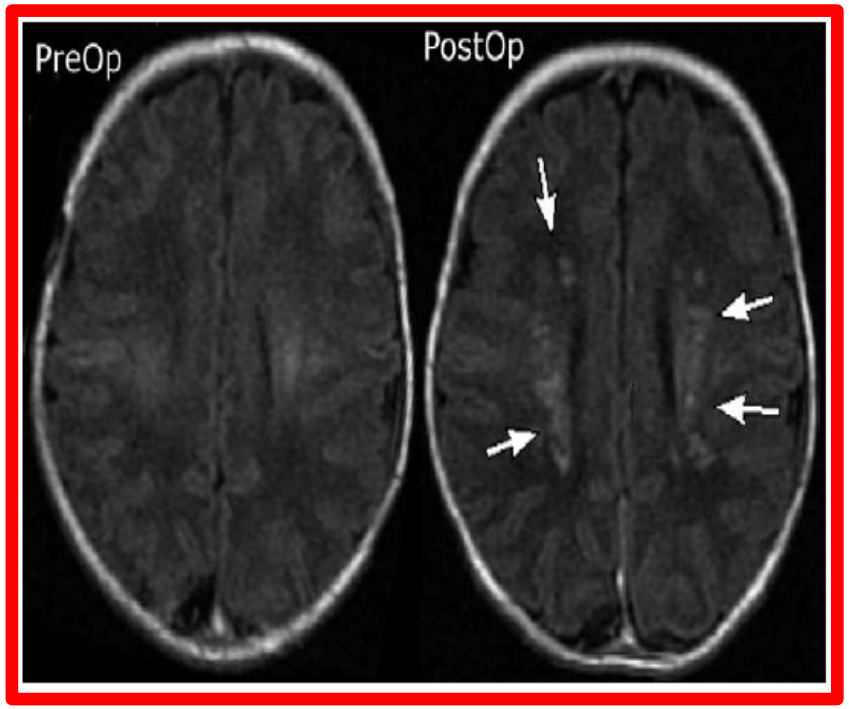
→ Rares,
→ Embols, hémorragies
→ Non dépistables en per op sauf massifs
→ Association pronostique?

Watersheed infarcts:

→ Liés à modification CBF prolongée
→ Dépistables

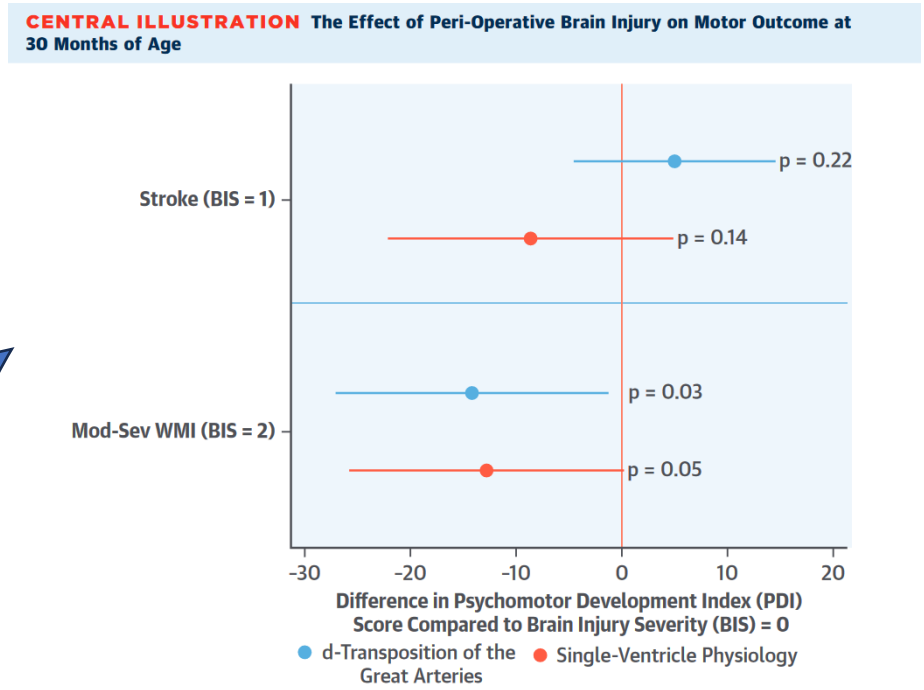


Multimodal **Ne**uro**Mo**nitoring during and After Neonatal **Cardi**ac Surgery

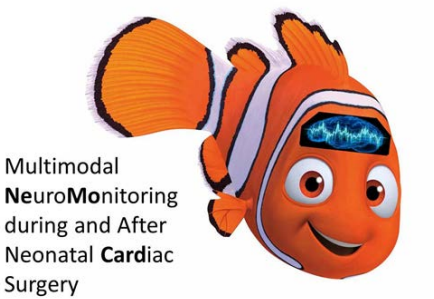


Perioperative WMI suggests Abrupt **variations of CBF**

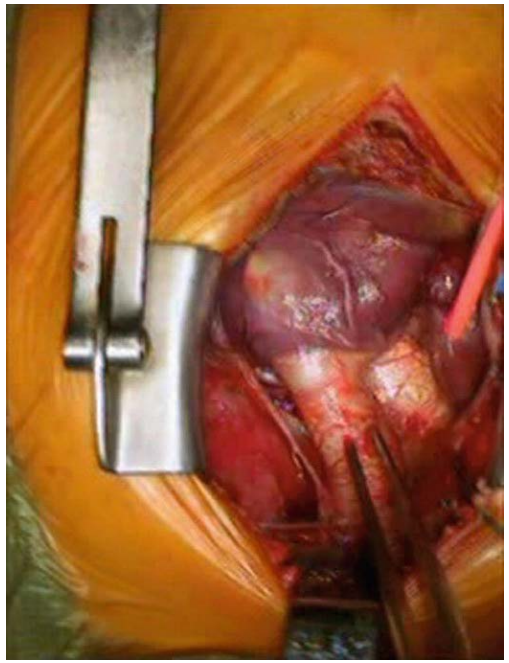
WMI and not Stroke are associated with late outcome

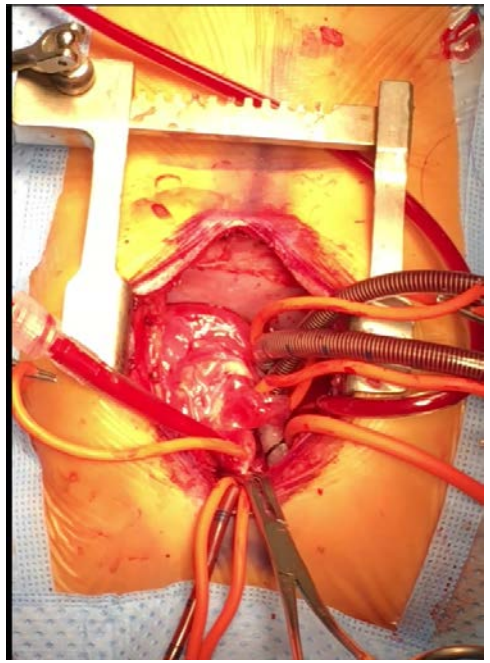


Peyvandi S et al JACC 2018
Peyvandi S er al JACC 2024



Multimodal
Neuro**Mo**nitoring
during and After
Neonatal **Card**iac
Surgery



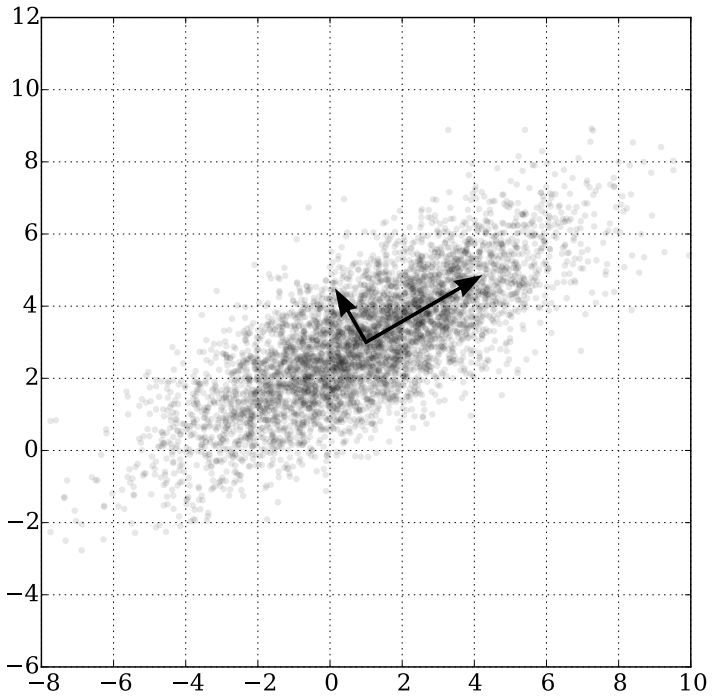


Challenges:

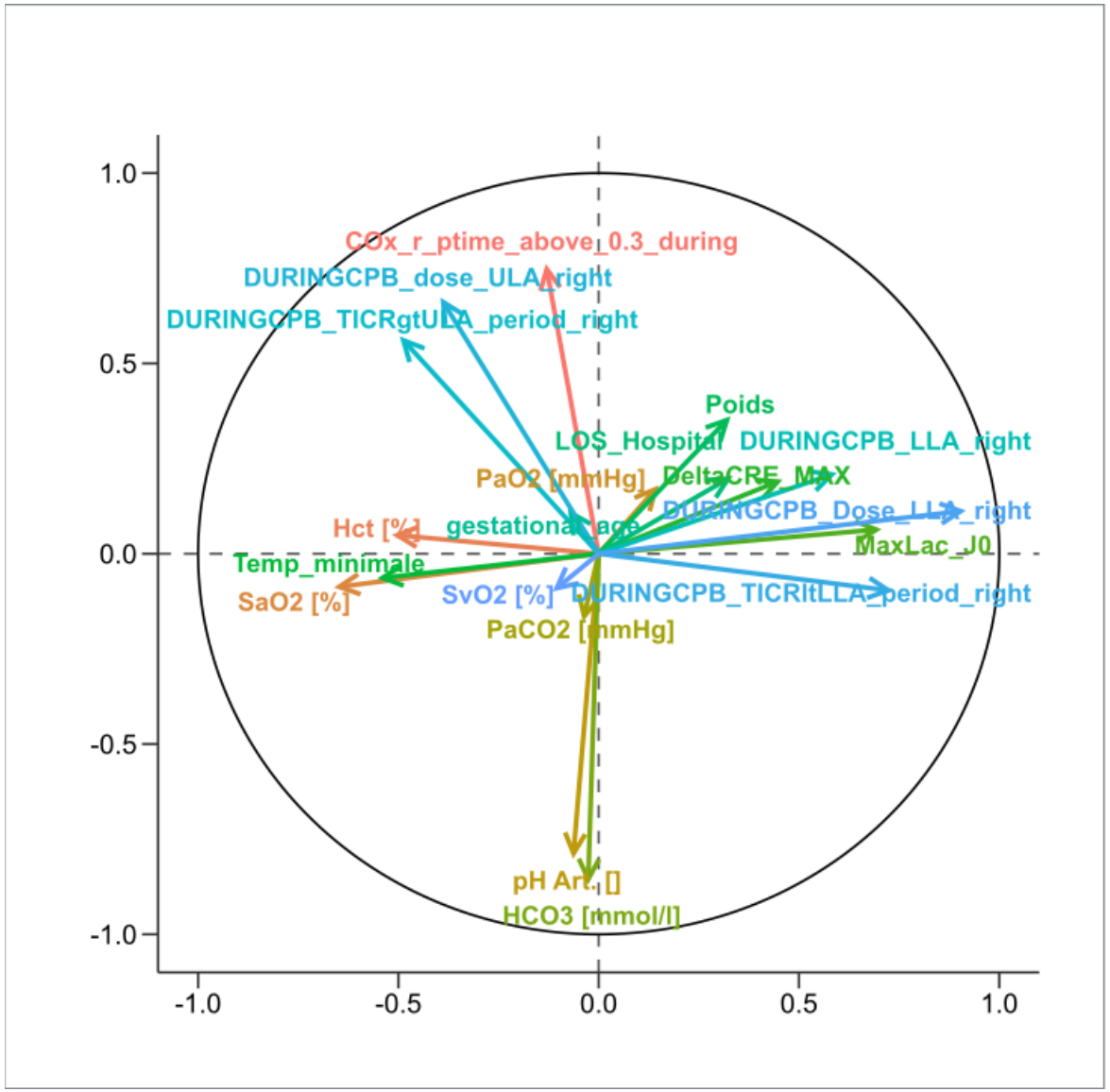
- Volume de priming: masse sanguine
- Hypothermie
- Cardioplégie
- pH vs α-stat
- Perfusion cérébrale sélective
- Variations intercenttres


Chris Barnard Division of
Cardiothoracic Surgery

Analyse exploratoire: Analyse en composante principale (PCA)



Réduit le nombre de dimensions dans les grands jeux de données, en composantes principales (=nouvelles variables ou Axes principaux



L'ESSENTIEL

	Component 1		
	Contribution 20.9147%		
	contrib.	coord.	cos2
DURINGCPB_Dose_LLA_right	20.5452	0.903562	0.816425
DURINGCPB_TICRltLLA_period_right	13.1551	0.723021	0.52276
MaxLac_J0	12.0788	0.692812	0.479989
SaO2 [%]	10.5521	-0.647549	0.419319
DURINGCPB_LLA_right	8.51834	0.581809	0.338502
Temp_minimale	7.32453	-0.539502	0.291062
Hct [%]	6.36324	-0.502854	0.252863
DURINGCPB_TICRgtULA_period_right	5.9779	-0.487391	0.23755
DeltaCRE_MAX	5.01925	0.446604	0.199455
DURINGCPB_dose_ULA_right	3.78541	-0.387846	0.150425
LOS_Hospital	2.63027	0.323298	0.104522
Poids	2.57721	0.32002	0.102413
PaO2 [mmHg]	0.503567	0.141459	0.0200108
COx_r_ptime_above_0.3_during	0.422529	-0.129578	0.0167905
SvO2 [%]	0.275654	-0.104661	0.0109539
gestational_age	0.121894	0.0695977	0.00484384

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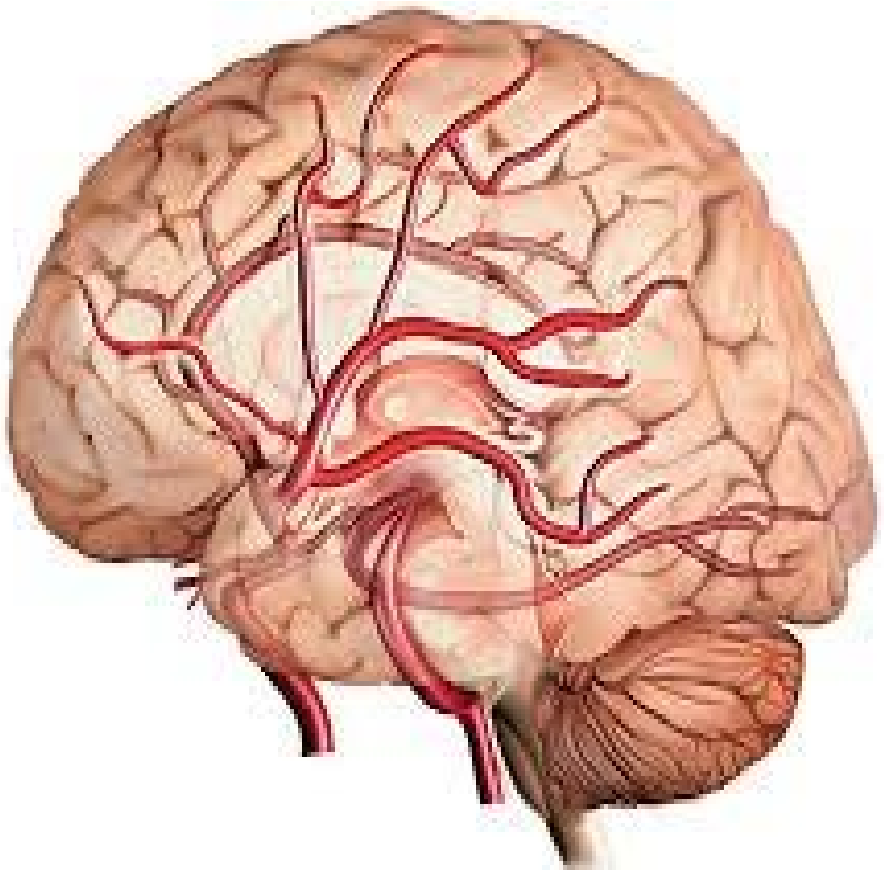
Débit Sanguin Cérébral

Débit Sanguin Cérébral (DSC)

→ Seule source d'O2
→ 15 à 30% de Qc (50 ml/100g/min)

→ DSC = PPC / RVC

→ PPC = PAM – (PVC + PIC)



Pediatric Anesthesia

Pediatric Anesthesia ISSN 1155-5645

REVIEW ARTICLE

Cerebral blood flow in the neonate

Laszlo Vutskits[1,2]

1 Department of Anesthesiology, Pharmacology and Intensive Care, University Hospital of Geneva, Geneva, Switzerland
2 Department of Fundamental Neuroscience, Geneva University Medical School, Geneva, Switzerland

Normal values of CBF in healthy volunteers: 40-50 ml/ 100g.min-1

Irreversible brain damage < 10 ml/100g.min-1

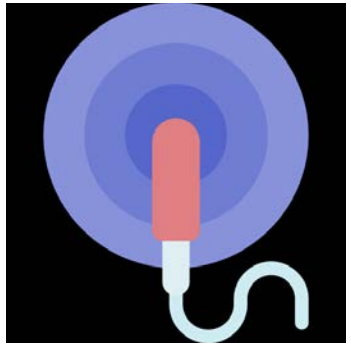
How to monitor CBF in the Bedside?

→ TCD
→ NIRS

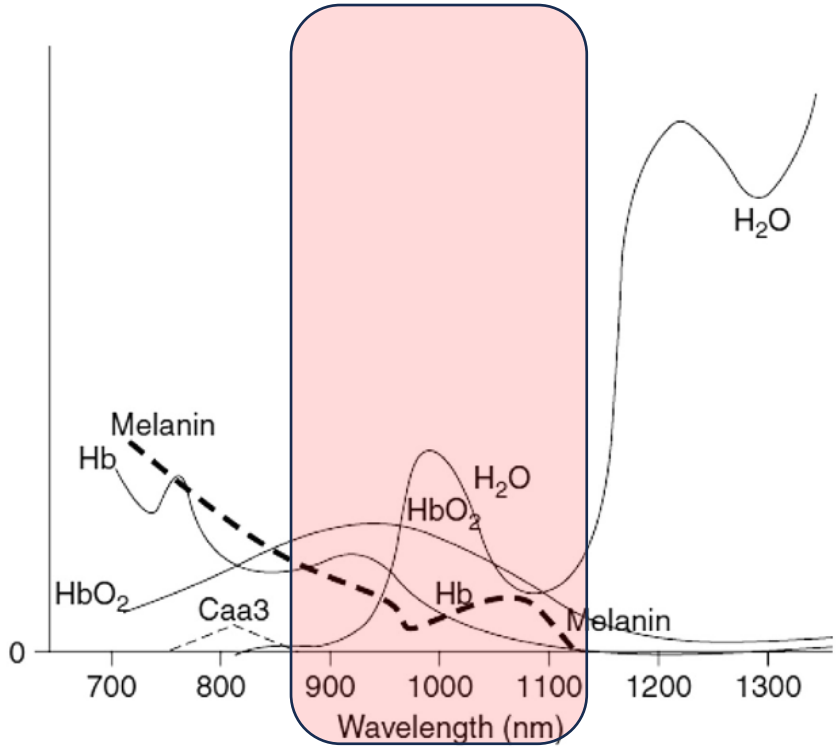
How to ensure adequat CBF during CPB?

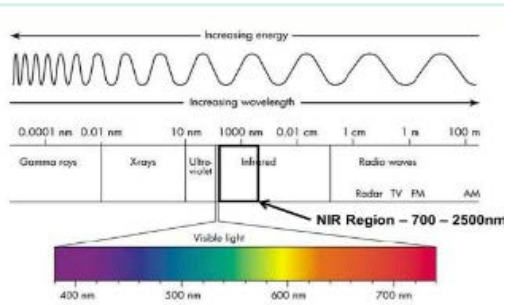
→ Optimal MAP? Optimal Blood flow?

Le (la) NIRS, de quoi parle-t-on?

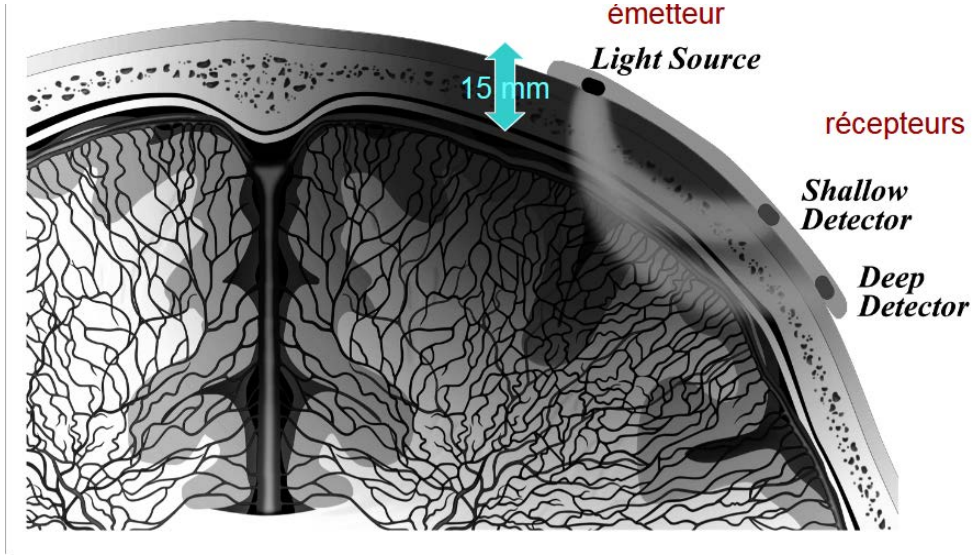


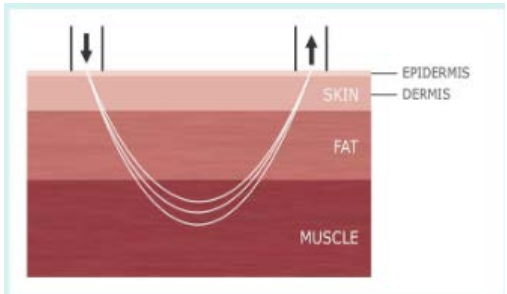
Loi de Beer Lambert: on mesure la concentration d'une substance selon son degré d'absorption de la lumière



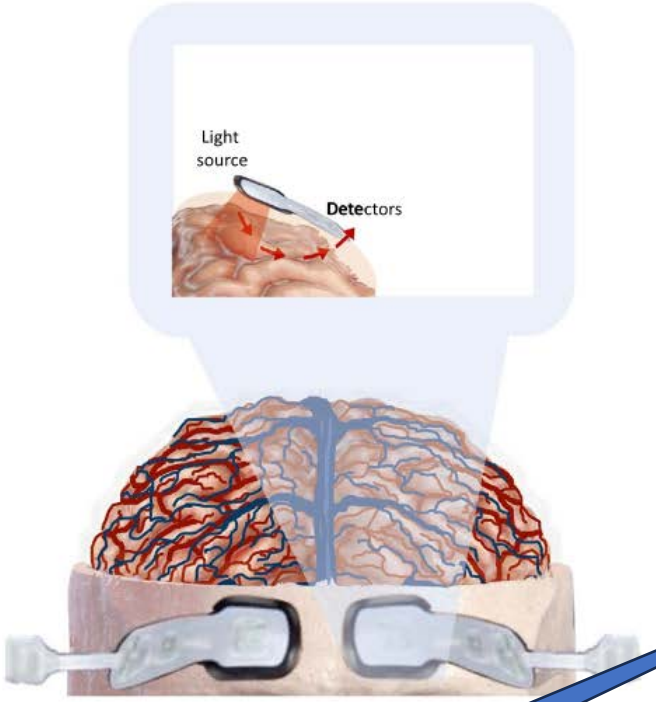


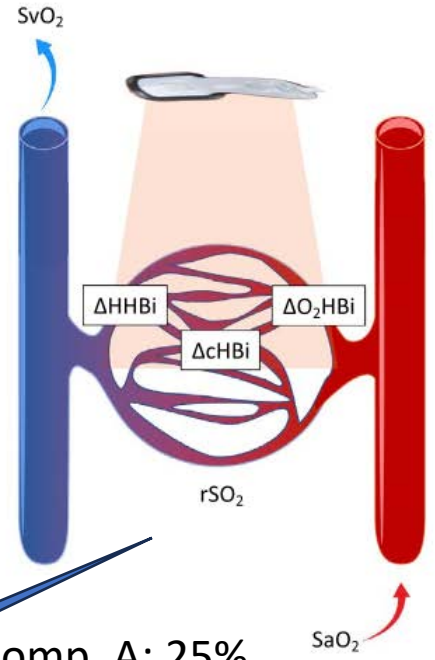
Limites: Hb < 6g/dL; Ht> 60%
Melanin





NN: Volume env. 1.5 cm3

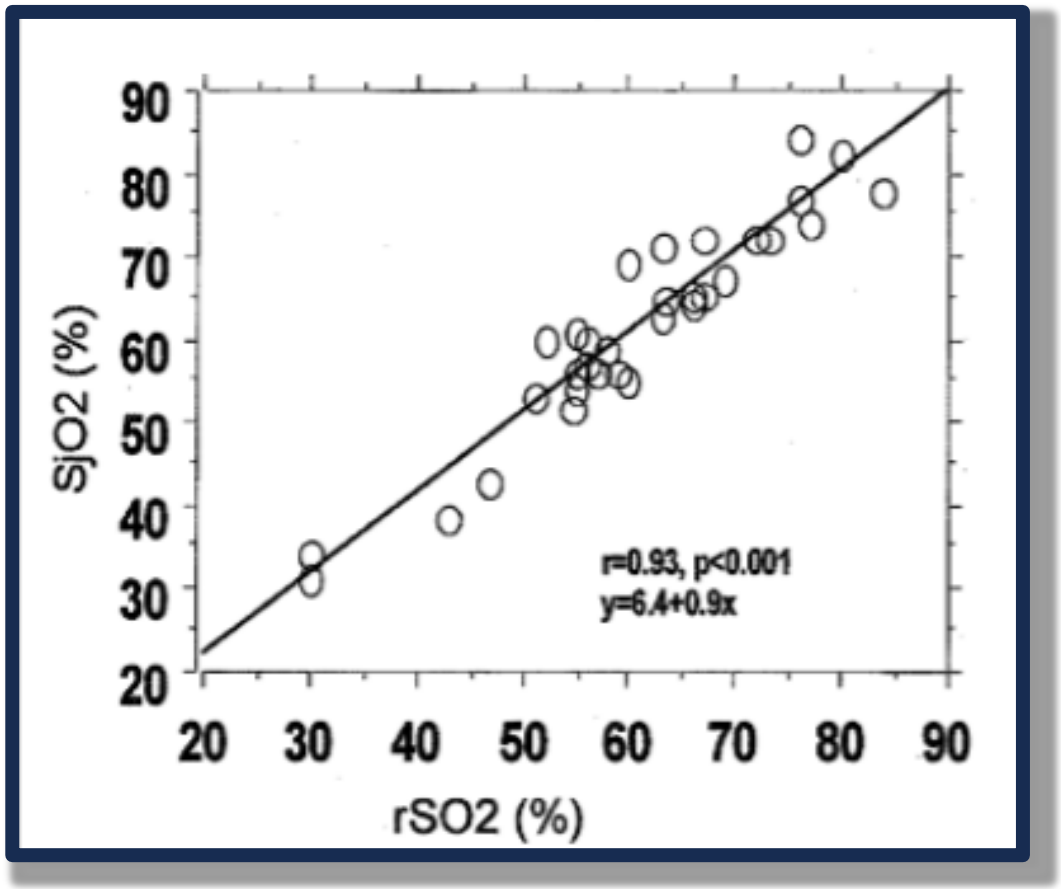


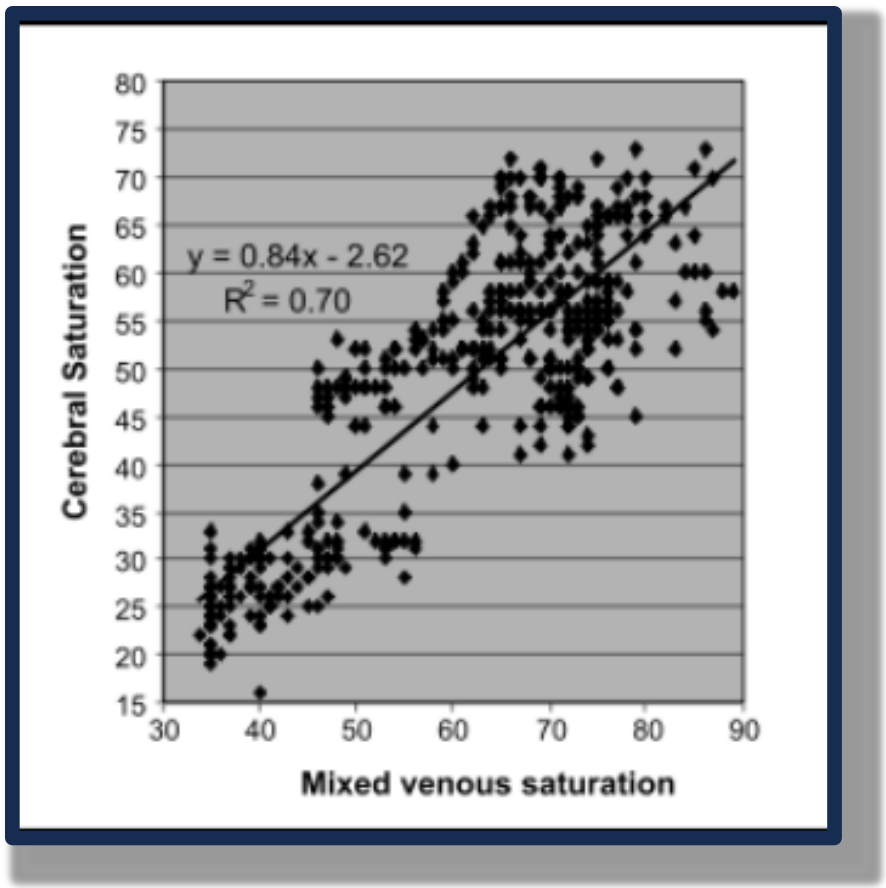


rSO2= $\frac{HbO2}{Hb}$

Comp. A: 25%
Comp. V: 75%

- ✓ **Oxygen consumption is 3.5 mL of oxygen/100 g tissue/1 min**
- ✓ **Extraction augmente si CBF chute (CMRO2= constant)**
- ✓ **CBF chute de 50%: dette en O2**





Kim et al, 2002

NIRS: surrogate of DO2

Pediatric Cardiac Surgery Annual

Noninvasive Assessment of Cardiac Output

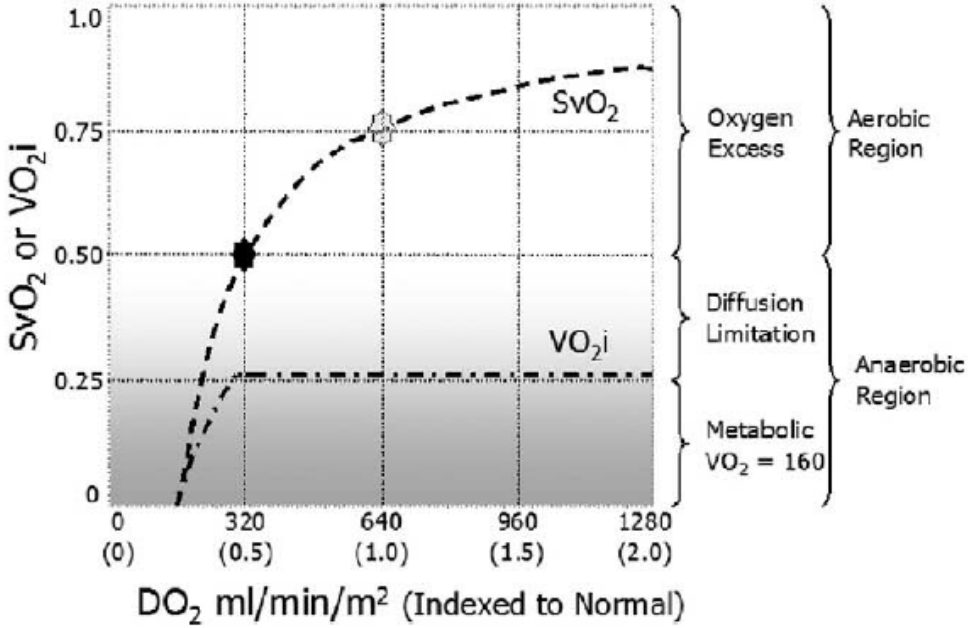
George M. Hoffman, Nancy S. Ghanayem, and James S. Tweddell

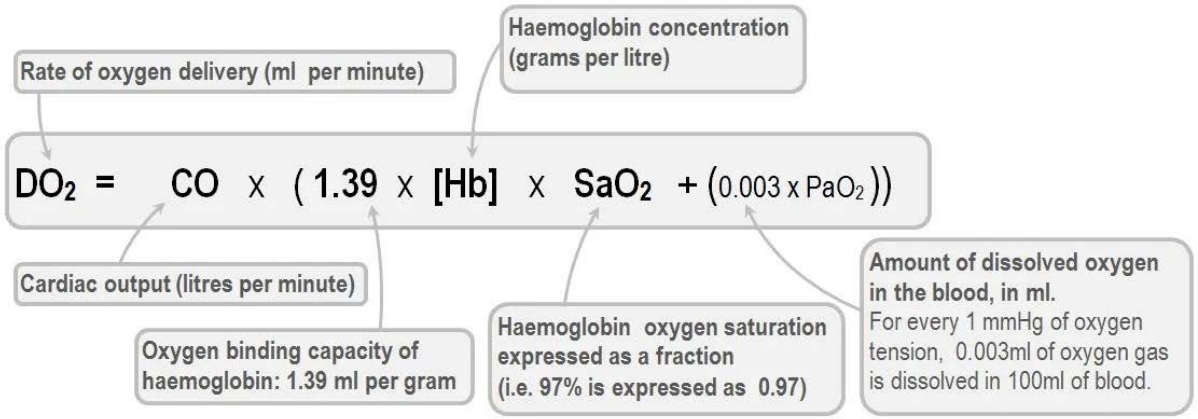
Improved outcome from shock depends on early detection and correction of circulatory abnormalities. Global cardiac output and oxygen delivery must be adequate and distributed appropriately to meet metabolic demands to prevent the development of multiple organ system dysfunction, prolonged morbidity, and death. Circulatory assessment using standard monitors gives incomplete and sometimes misleading information. This article focuses on the available and emerging technologies that emphasize assessment of blood flow and regional tissue oxygenation.

Semin Thorac Cardiovasc Surg Pediatr Card Surg Ann 8:12-21

KEYWORDS: SvO_2 (mixed venous saturation), cardiac output, hemodynamic monitoring, near-infrared spectroscopy, shock

Hoffman G 2005





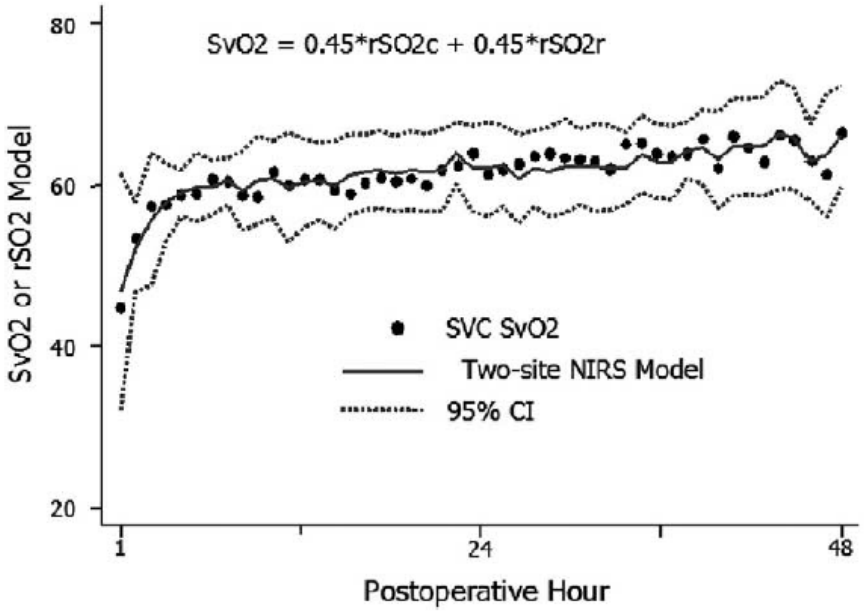


Figure 11 The two-site NIRS model shows good prediction of Sv^{o}_{2} for within-patient trends.

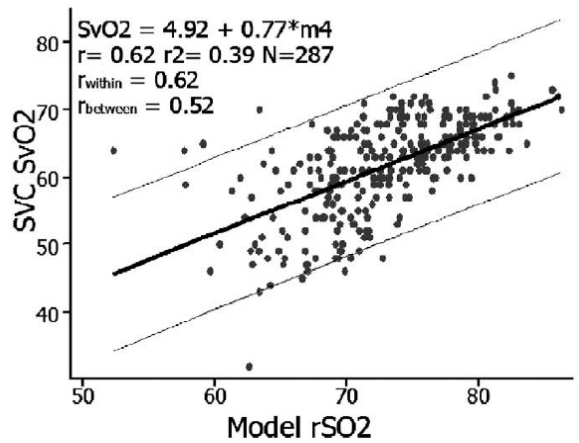
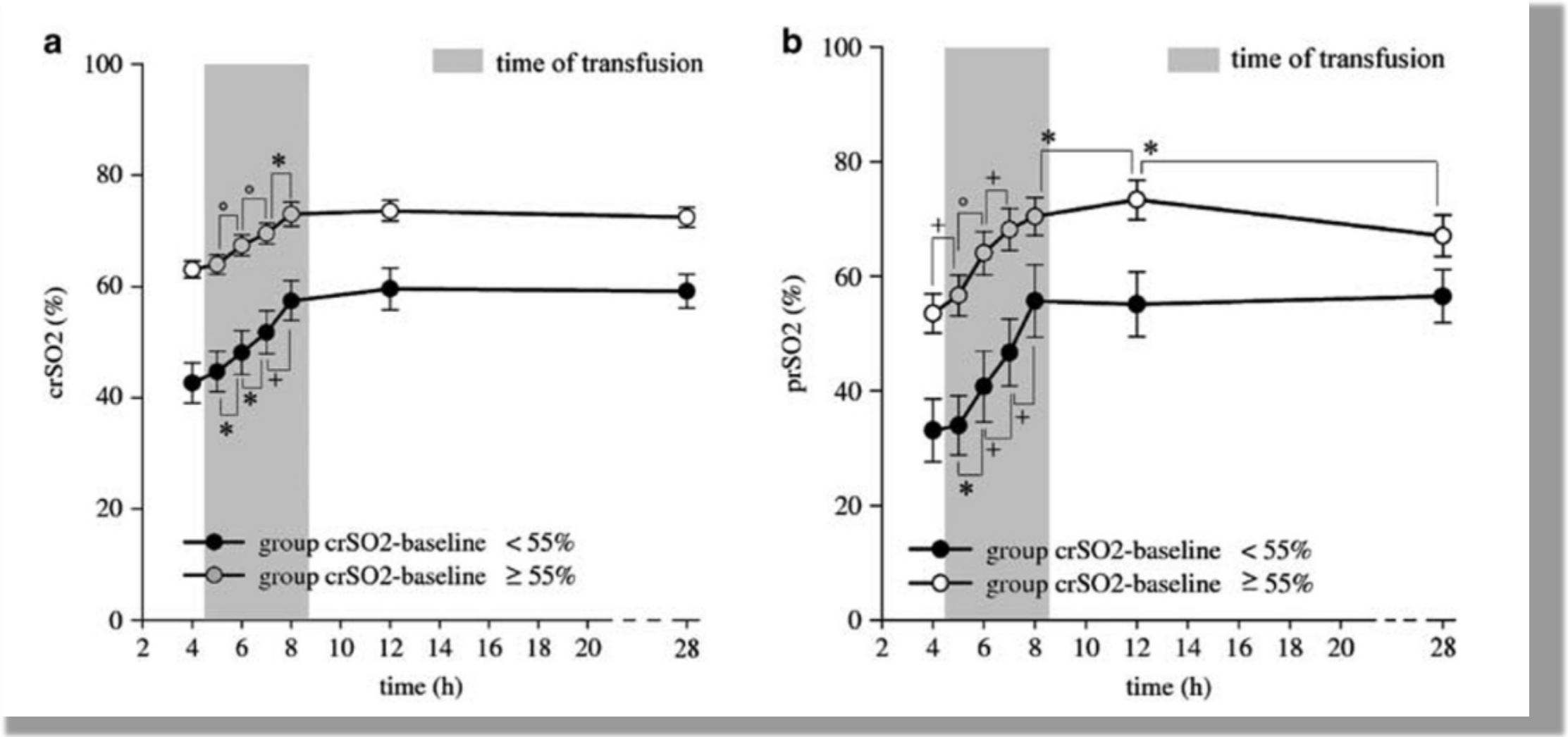
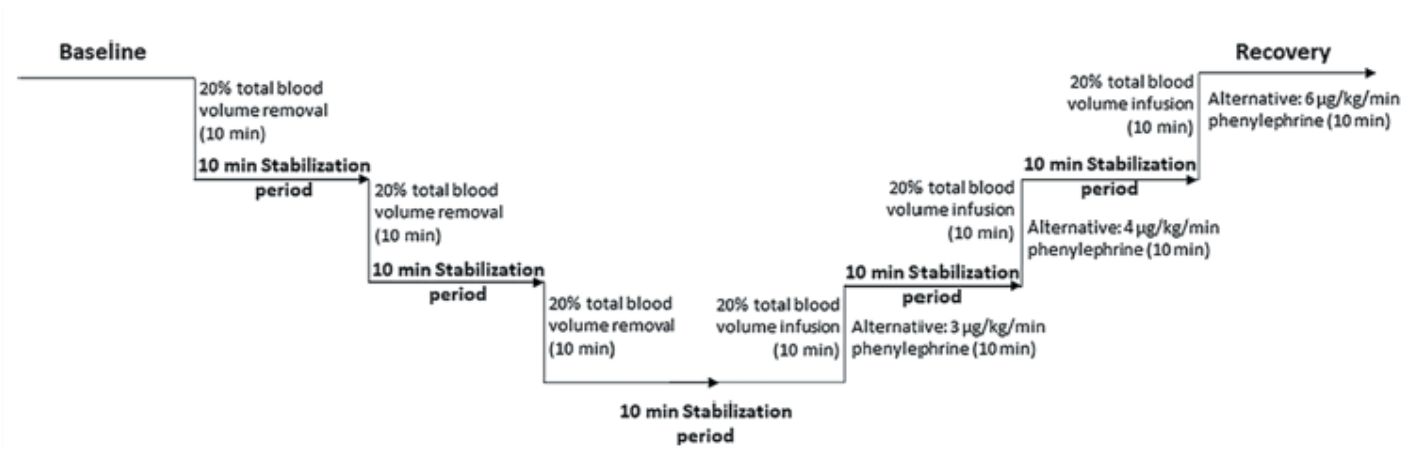


Figure 10 A linear combination of cerebral and somatic rSo_2 provided a better approximation of Svo_2 than either alone.



Seidel, J Perinat 2013



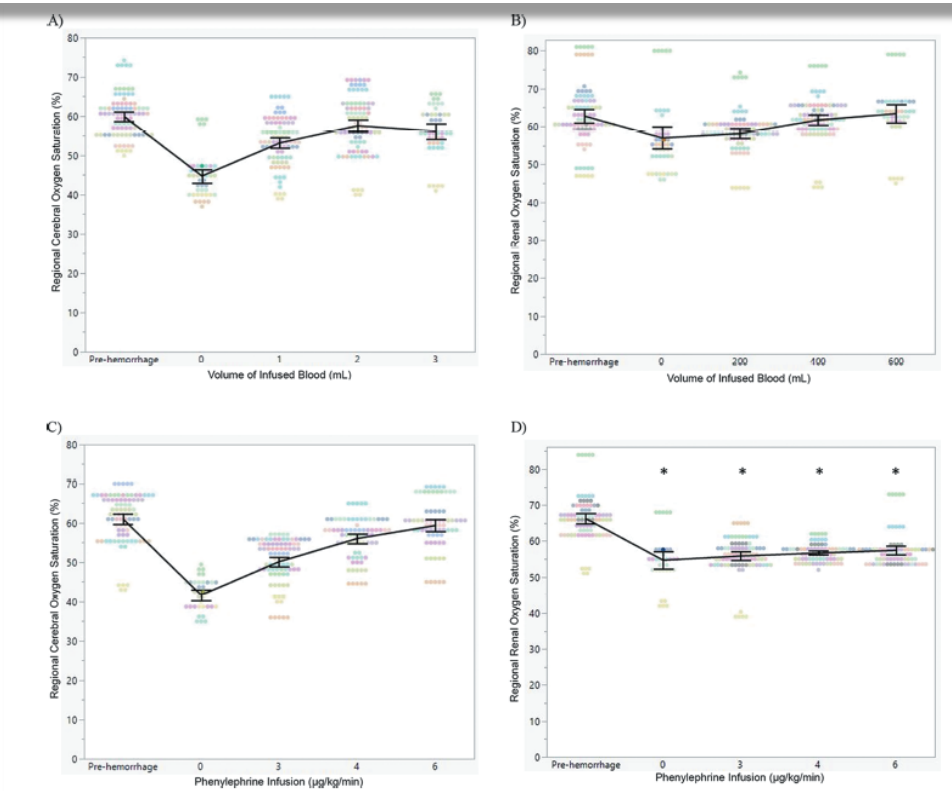
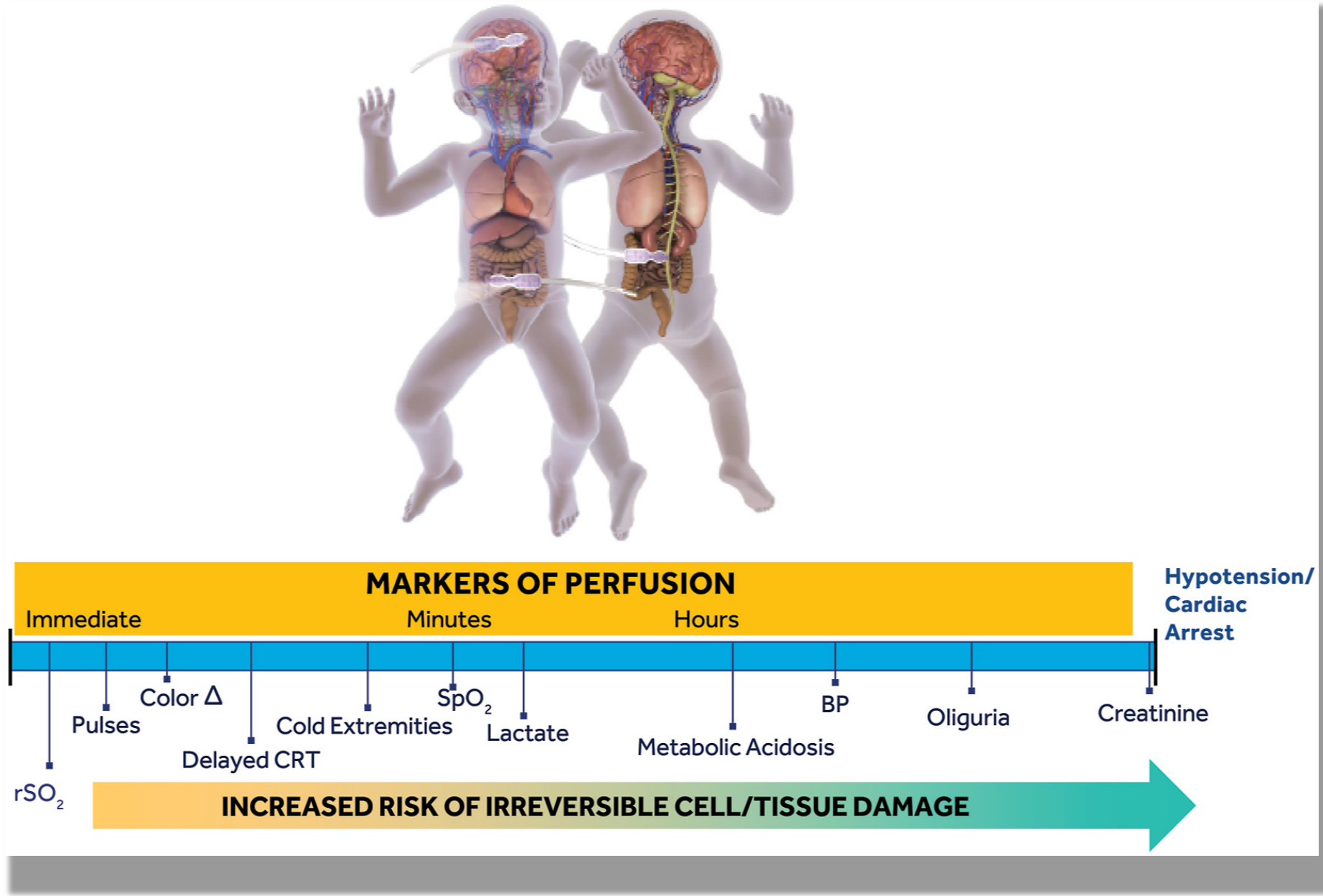
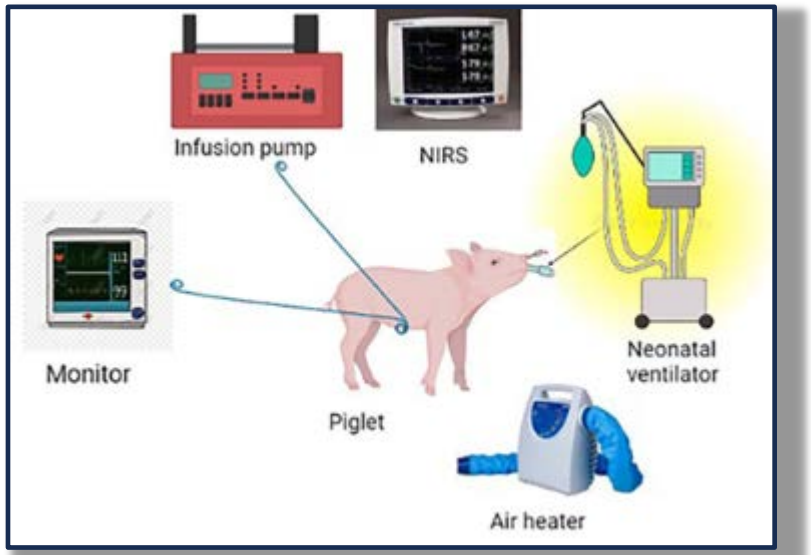


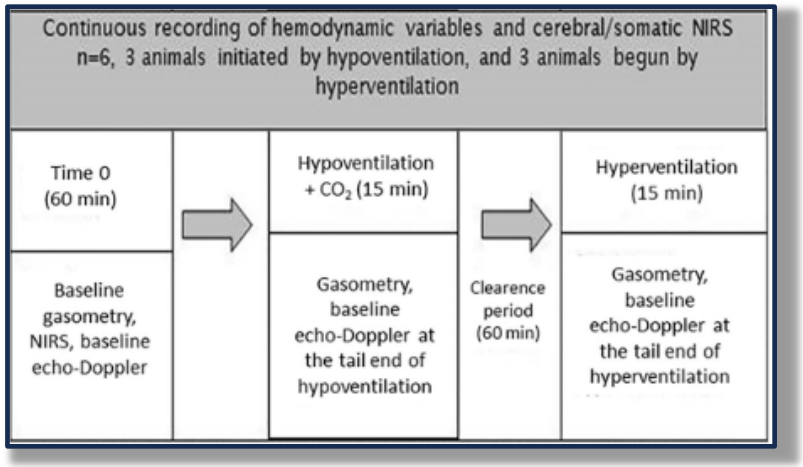
FIGURE 2. (A) Regional cerebral oxygen saturation during resuscitation by blood infusion, (B) $RrSO_2$ during resuscitation by blood infusion, (C) $CrSO_2$ during blood pressure management using phenylephrine infusion, and (D) $RrSO_2$ during blood pressure management using phenylephrine infusion. Data clusters reflect the five repeat measurements performed for each subject during each procedure step. The line represents the mean percent $CrSO_2$ or $RrSO_2$ across all measurements, with 95% CIs. Statistical significance relative to baseline (pre-hemorrhage) is denoted as * representing $P < .0001$. Abbreviations: $CrSO_2$, regional cerebral oxygen saturation; $RrSO_2$, regional cerebral oxygen saturation.

Borg U. Mil Med 2023



J Clin Nurse North America 2022





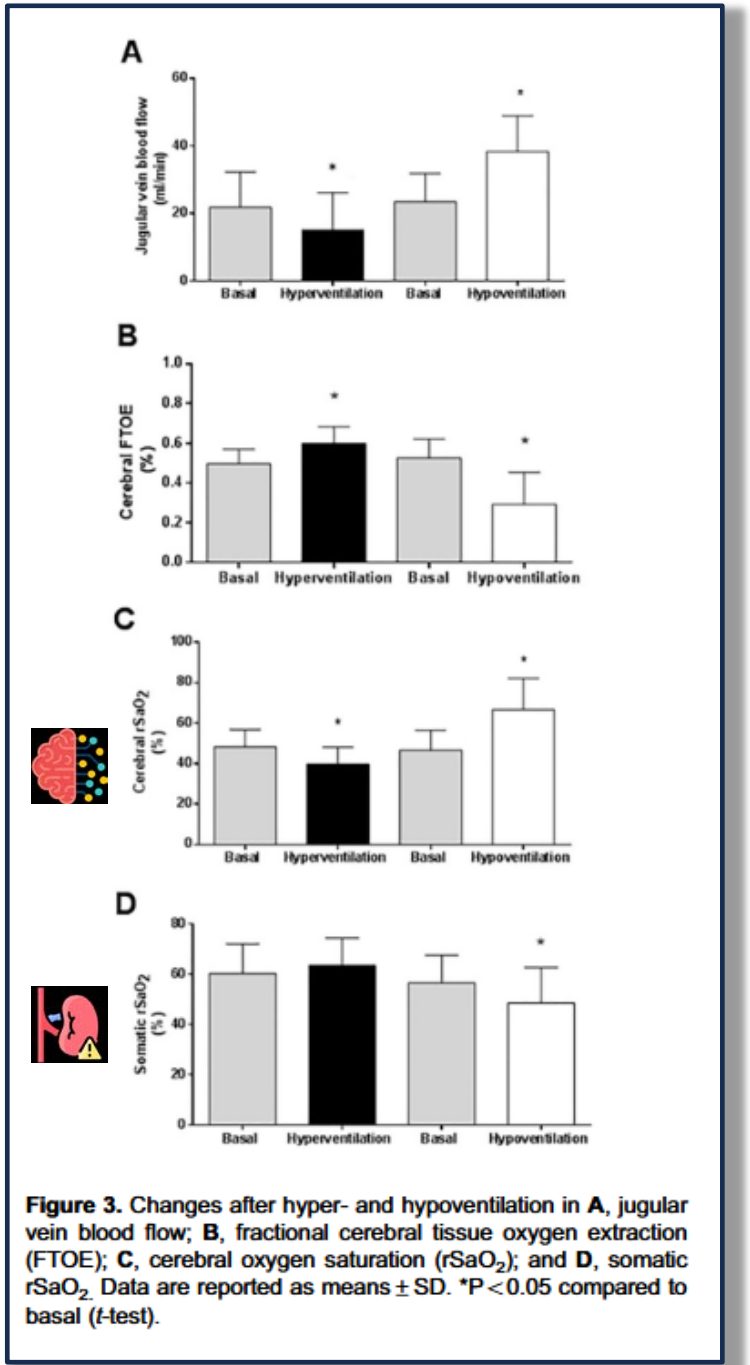


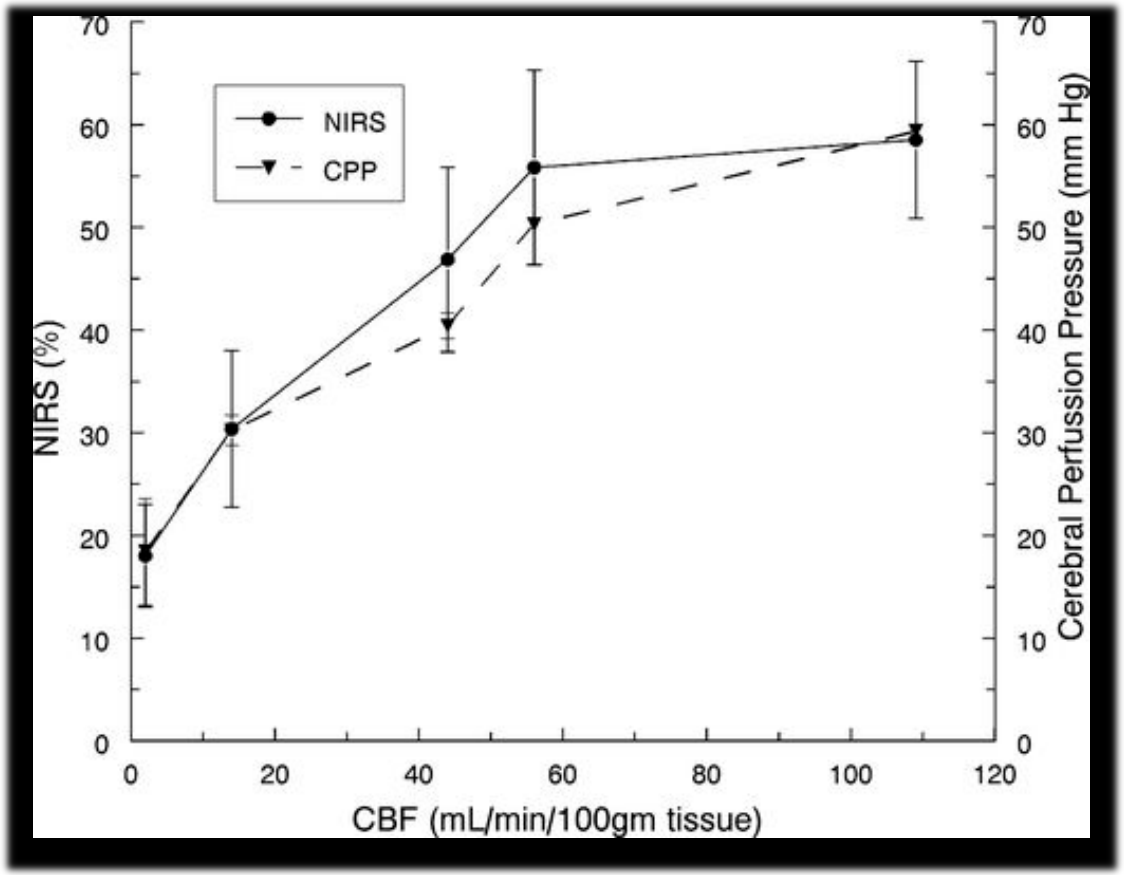
Figure 3. Changes after hyper- and hypoventilation in **A**, jugular vein blood flow; **B**, fractional cerebral tissue oxygen extraction (FTOE); **C**, cerebral oxygen saturation ($rSaO_2$); and **D**, somatic $rSaO_2$. Data are reported as means ± SD. *$P < 0.05$ compared to basal (*t*-test).

Silvera, J Med Biol research 2022

NIRS: surrogate of CBF

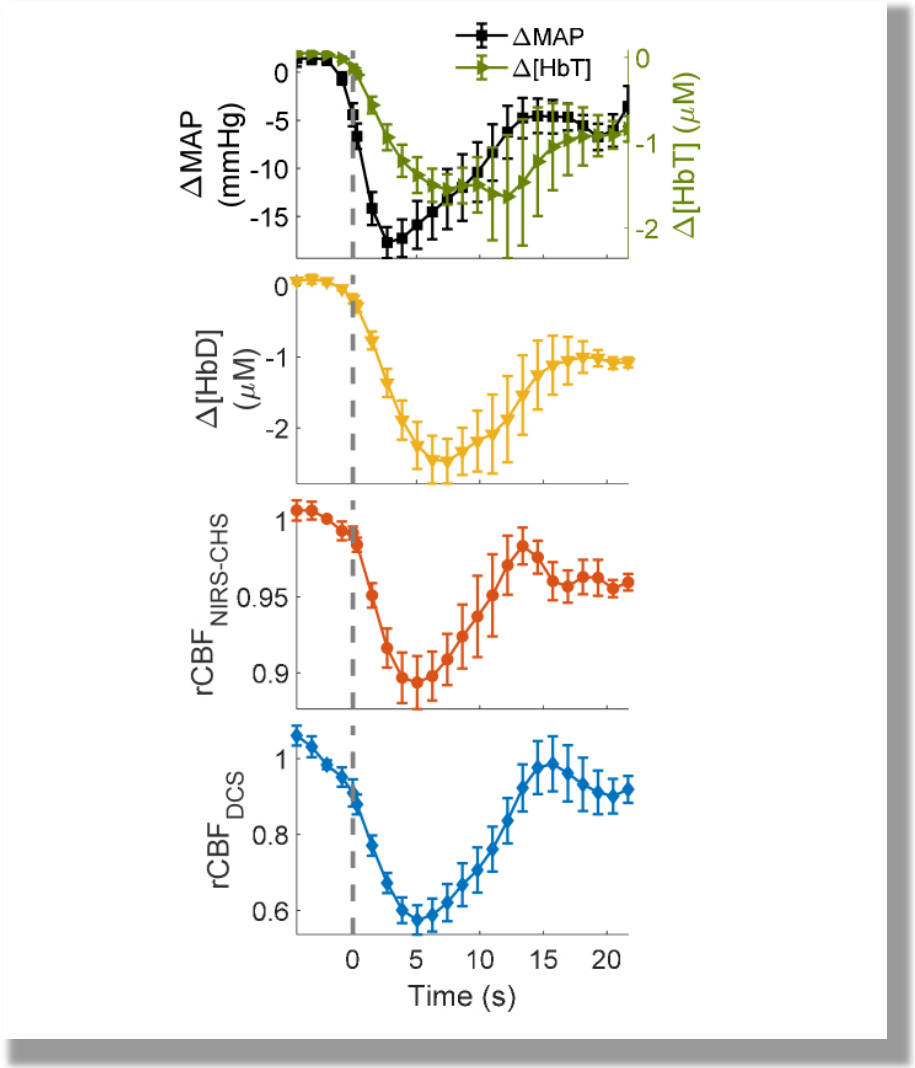
The correlation between brain near-infrared spectroscopy and cerebral blood flow in piglets with intracranial hypertension
Alosh et al, J Appl Physiol 1985

→ *à PaCO2 constante, SaO2 constante,*
Qc constant et [Hb] constant, le volume total
D'Hb ne peut varier que par variation du DSC



Quantitative measurements of cerebral blood flow with near-infrared spectroscopy

$$\mathrm{CBF}_0 = \frac{1}{\rho_b}\frac{\mathscr{F}^{(c)}\mathrm{CBV}_0^{(c)}}{t^{(c)}} = \frac{1}{\rho_b}\frac{[\mathrm{HbT}]_0}{\mathrm{ctHb}}\frac{\frac{\mathscr{F}^{(c)}\mathrm{CBV}_0^{(c)}}{\mathrm{CBV}_0}}{t^{(c)}}$$



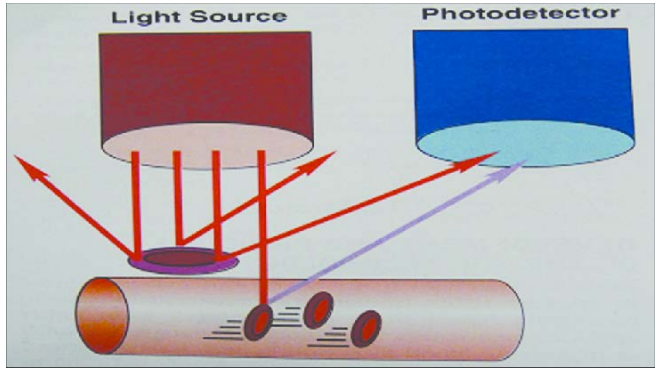
Pham T, 2019

Continuous Time-Domain Analysis of Cerebrovascular Autoregulation Using Near-Infrared Spectroscopy *Stroke 2007*

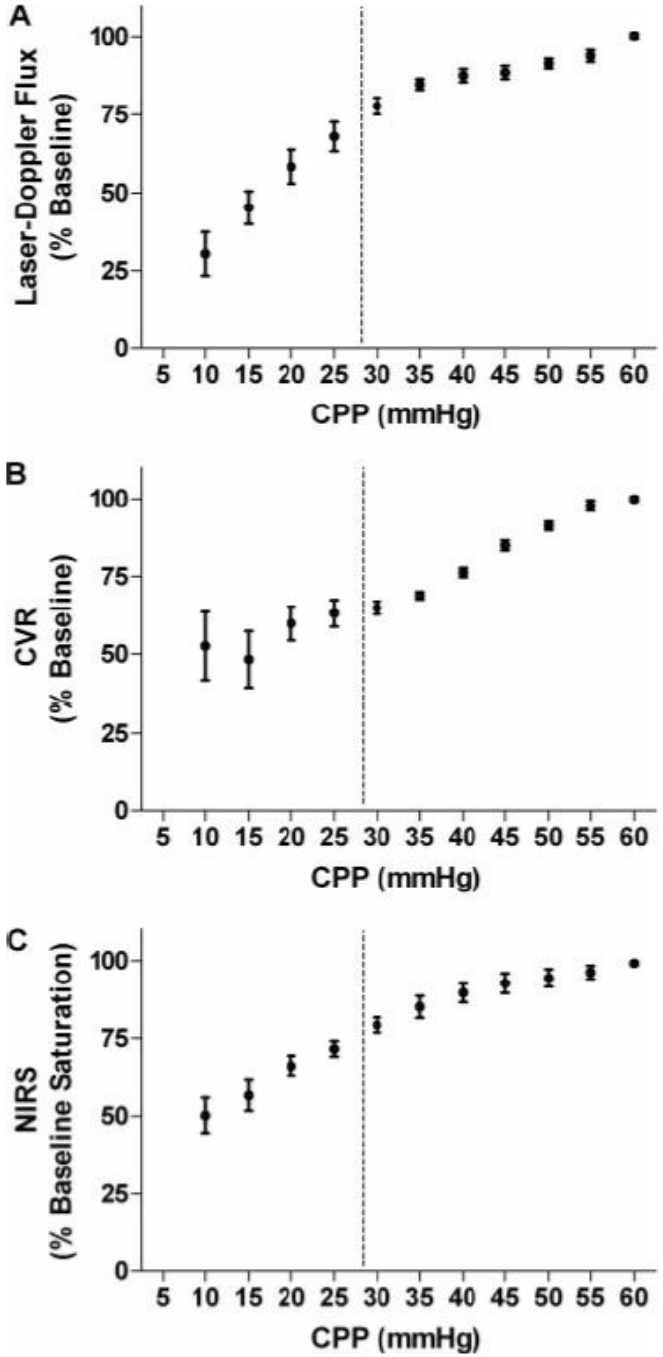
Ken M. Brady, MD, **Jennifer K. Lee, MD**, **Kathleen K. Kibler, BS**, **Piotr Smielewski, PhD**, **Marek Czosnyka, PhD**, **R. Blaine Easley, MD**, **Raymond C. Koehler, PhD**, and **Donald H. Shaffner, MD**

Department of Anesthesiology and Critical Care Medicine (K.M.B., J.K.L., K.K.K., R.B.E., R.C.K., D.H.S.), Johns Hopkins University School of Medicine, Baltimore, Md; and the Department of Academic Neurosurgery (P.S., M.C.), Addenbrooke's Hospital, Cambridge, UK.

- ✓ 6 piglets
- ✓ Laser Doppler: Gold Standard measure



- → NIRS may be used as a surrogate of CBF to determine LLA (Static measurement here)
- → The study highlights the association of MAP and NIRS value!



Cerebral Oxygen Saturation-Time Threshold for Hypoxic-Ischemic Injury in Piglets

cRSO2 restauré qqsoit la durée d'HIE

Modèle HIE-Reperfusion.
Modèle: cRSO2 35-40%

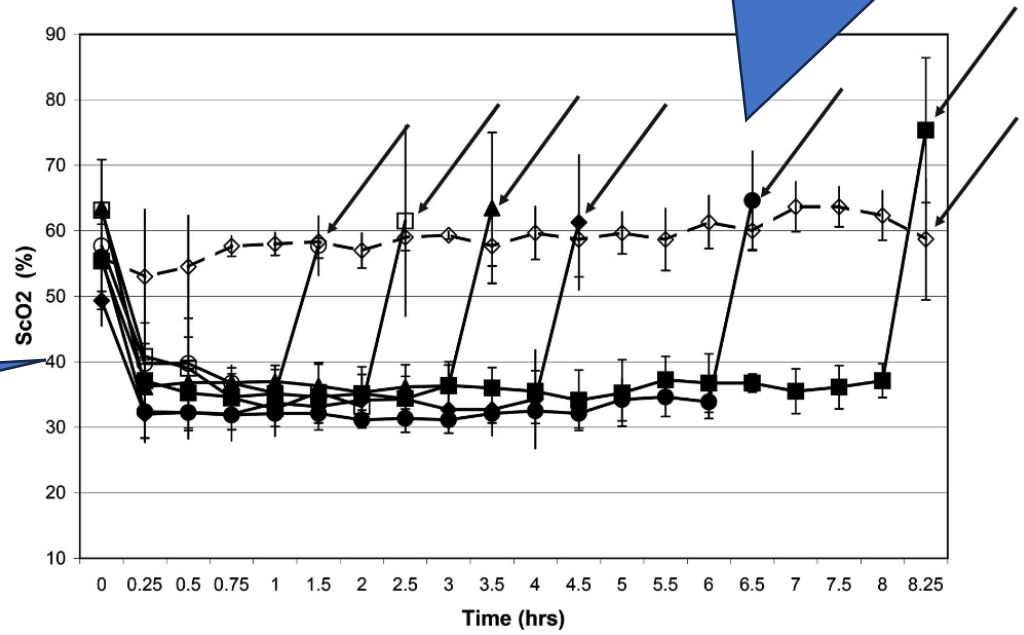


Figure 1. Cerebral O_2 saturation (Sc_{O2}) during the study in each group. Control group (◇-◇) received anesthesia without hypoxia-ischemia (H-I). Other groups experienced episodes of 1 h H-I (o-o), 2 h H-I (□-□), 3 h H-I (▲-▲), 4 h H-I (◆-◆), 6 h H-I (·-·), or 8 h H-I (■-■) while anesthetized. Time 0 is baseline. During H-I, Sc_{O2} was targeted to 35%. Reperfusion after H-I is indicated by the arrow. In the control group, arrow indicates recovery after discontinuing anesthesia. Values are mean ± SD, n = 4 to 8 in each group.

Kurth D, Anest Analg 2009

Cerebral Oxygen Saturation-Time Threshold for Hypoxic-Ischemic Injury in Piglets

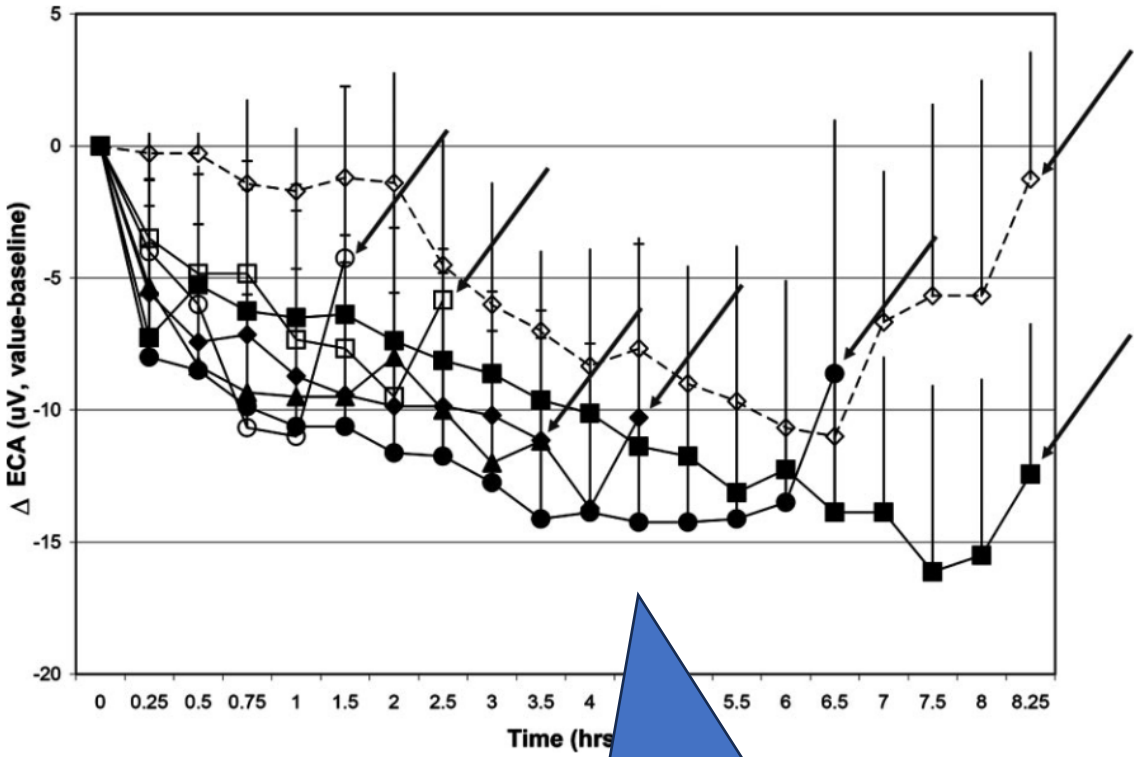


Figure 4. Electrocortical activity (ECA) during the study relativ ECA as measured by trough value on the cerebral function monitor in each group. Groups and symbols s Baseline is before H-I.

Fonction cérébrale (CFM-aEEG) en fonction du temps d'ischémie (cRSO2 35-40%)

Kurth D, Anest Analg 2009

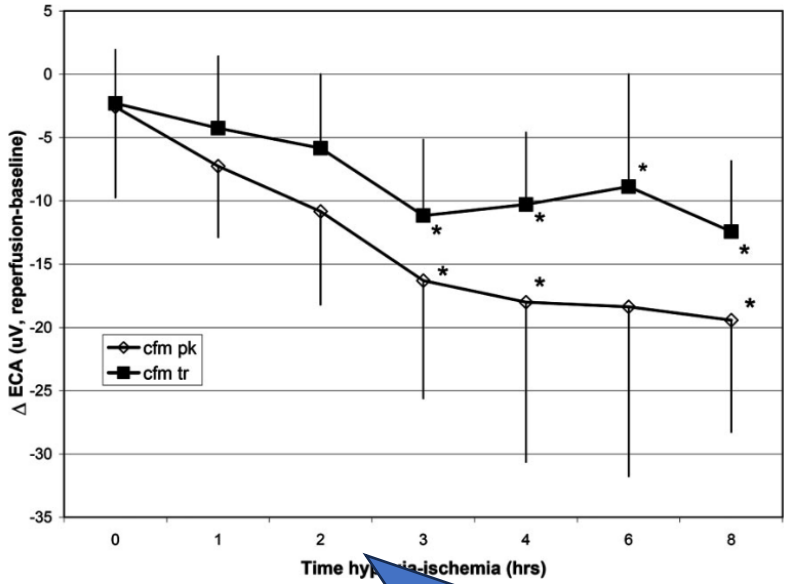


Figure 5. Electrocortical activity during reperfusion relative lectrocortical activity (ΔECA) as measured by the peak and trough values on the cerebral function monitor (cfm arying duration of hypoxia-ischemia (H-I). The control group is indicated by 0 h of H-I. * is $P < 0.05$ vs co

Lésions neuronales critiques à H2

Low-Flow Cardiopulmonary Bypass: Importance of Blood Pressure in Maintaining Cerebral Blood Flow

Robert E. Michler, MD, Aqeel A. Sandhu, MD, William L. Young, MD, and Arthur E. Schwartz, MD

Cardiac Transplantation Research Laboratory, Departments of Surgery and Anesthesia, Columbia University College of Physicians & Surgeons, and Cardiothoracic Surgery and Anesthesiology Services, Presbyterian Hospital in the City of New York, New York, New York

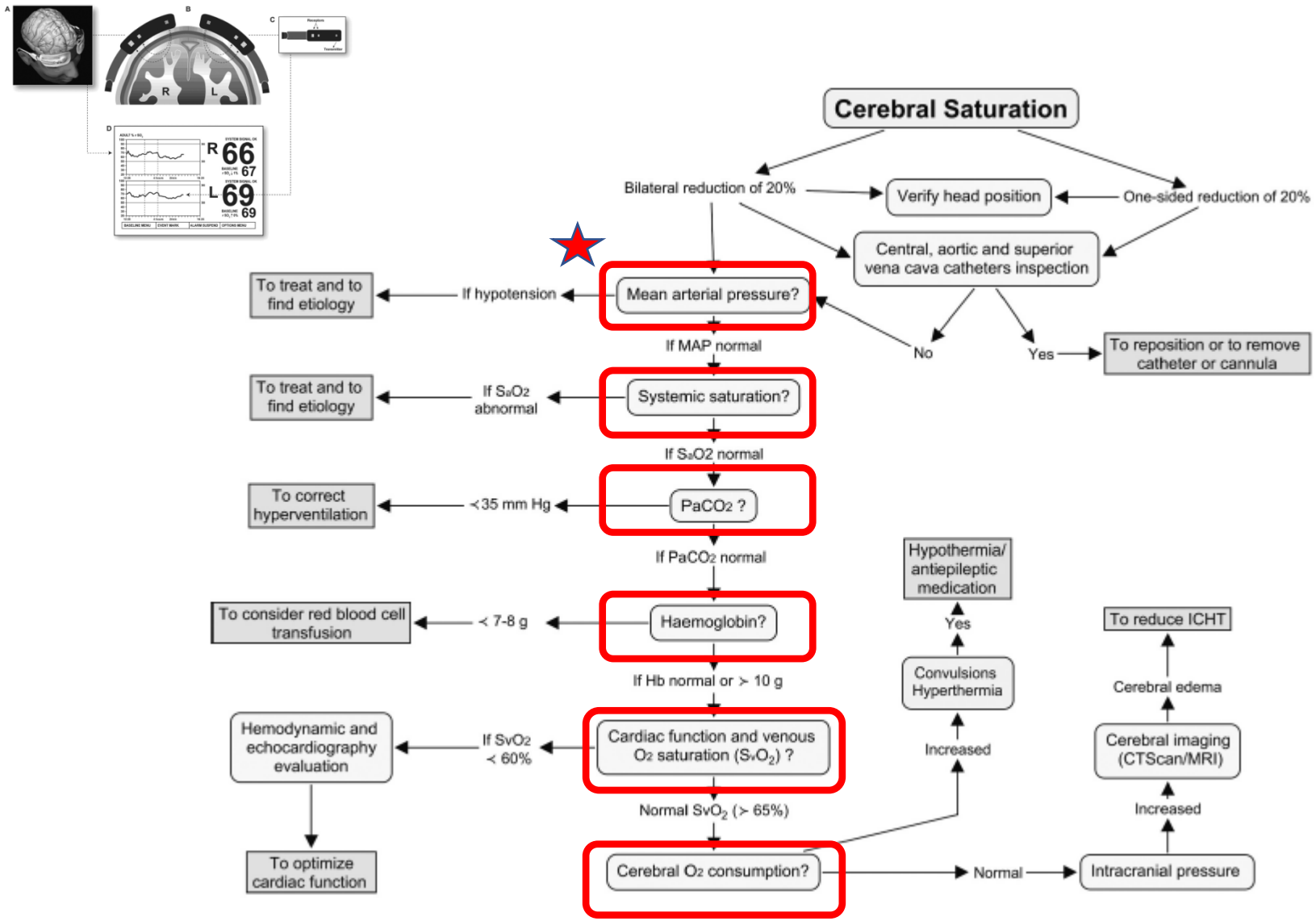
Table 1. Physiologic Variables Before and During Cardiopulmonary Bypass[a]

Variable	Before Bypass	Full-Flow CPB		Low-Flow CPB	
		High BP	Low BP	High BP	Low BP
CBF (mL · min $^{-1}$ · 100 g $^{-1}$)	26.0 ± 3.1	27.6 ± 9.9	16.8 ± 3.7[b]	34.0 ± 8.3	14.1 ± 3.7[b]
A-VO_2 (mL/100 mL)	5.1 ± 1.7[b]	2.5 ± 1.3	3.0 ± 1.8	2.2 ± 0.9	3.3 ± 0.5
$CMRO_2$ (mL · min $^{-1}$ · 100 g $^{-1}$)	1.2 ± 0.4[b]	0.68 ± 0.40	0.49 ± 0.25	0.70 ± 0.20	0.44 ± 0.20
MABP (mm Hg)	69 ± 13	61 ± 2	24 ± 3	62 ± 2	23 ± 3
Pump flow (L · min $^{-1}$ · m $^{-2}$)	. . .	2.23 ± 0.06	2.23 ± 0.06	0.75	0.75
Temperature (°C)	35 ± 0.8	27.7 ± 0.4	27.7 ± 0.5	27.7 ± 0.5	27.8 ± 0.4
pCO_2 (mm Hg)	33 ± 4	34 ± 2	33 ± 2	36 ± 4	36 ± 3
pH	7.48 ± 0.03[c]	7.42 ± 0.04	7.43 ± 0.07	7.41 ± 0.05	7.41 ± 0.04
pO_2 (mm Hg)	499 ± 31[d]	377 ± 128	382 ± 115	431 ± 95	425 ± 112
Hematocrit	30 ± 3[b]	16 ± 4	16 ± 4	16 ± 3	16 ± 4

[a] Values are mean ± standard deviation; arterial blood gas analyses were performed at 37°C. [b] $p < 0.01$ compared with others. [c] $p < 0.05$ compared with others. [d] $p < 0.05$ compared with full-flow high BP, full-flow low BP, low-flow low BP.

A-VO_2 = cerebral arteriovenous oxygen content difference; CPB = cardiopulmonary bypass; CBF = cerebral blood flow; $CMRO_2$ = cerebral oxygen metabolic rate; MABP = mean arterial blood pressure; pCO_2 = carbon dioxide tension; pO_2 = oxygen tension.

Murkin Protocole 2008. NIRS-based Algorithm



Rappel: Evaluation d'un dispositif de monitoring/ Outil diagnostic

1

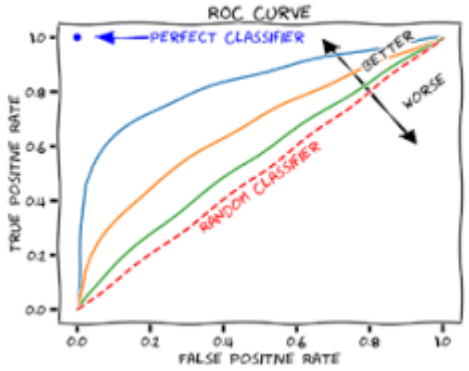
- Déterminer une **valeur pronostique**
- Etude observationnelle prospective. Preuve de concept. En aveugle. Critère de jugement sensibles (marqueurs biologiques, imagerie).

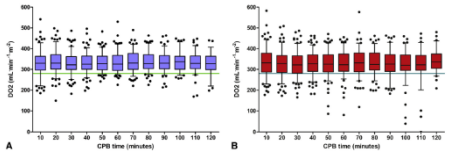
2

- Déterminer un **impact dans la prise en charge**: l'outil modifie t il la pratique et de quelle manière?
- Etude observationnelle randomisée avec choix du critère de jugement principal sensible (exemple: modification de pratique, marqueurs biologiques)

3

- Prouver un **bénéfice clinique**
- Etude interventionnelle randomisée dont le bras interventionnel utilise l'outil (algorithme de prise en charge) et le groupe témoin est une pratique standard. Evaluation en aveugle du groupe de randomisation.





Cochrane Library

Cochrane Database of Systematic Reviews

Cerebral near-infrared spectroscopy (NIRS) for perioperative monitoring of brain oxygenation in children and adults (Review)

Yu Y, Zhang K, Zhang L, Zong H, Meng L, Han R

Open Access Research

BMJ Open

Effects of cerebral near-infrared spectroscopy on the outcome of patients undergoing cardiac surgery: a systematic review of randomised trials

Giuseppe Filiberto Serraino, Gavin J Murphy

Table 3 Summary of main findings of systematic review and GRADE assessment of trial results

Near-infrared spectroscopy algorithm compared with control (standard care) in cardiac surgery

Patient population: adult cardiac surgery; setting: tertiary cardiac centres

Intervention: near-infrared spectroscopy algorithms for personalised optimisation of cerebral oxygenation

Control: standard care

Outcomes	Anticipated absolute effects* (95% CI)		Relative effect (95% CI)	Participants (n) (studies)	Quality of the evidence (GRADE)
	Risk with control	Risk with NIRS			
Mortality	32 per 1000	25 per 1000 (10 to 63)	RR 0.76 (0.30 to 1.96)	608 (4 RCTs)	⊕⊕◯◯ Low
Red cell transfusion	504 per 1000	469 per 1000 (388 to 564)	RR 0.93 (0.77 to 1.12)	744 (4RCTs)	⊕⊕◯◯ Low
Stroke	16 per 1000	17 per 1000 (6 to 46)	RR 1.08 (0.40 to 2.91)	1138 (7 RCTs)	⊕◯◯◯ Very low
Myocardial infarction	29 per 1000	26 per 1000 (12 to 54)	RR 0.90 (0.43 to 1.89)	1038 (6 RCTs)	⊕◯◯◯ Very low
Renal failure	71 per 1000	62 per 1000 (41 to 95)	RR 0.88 (0.58 to 1.34)	1043 (6 RCTs)	⊕◯◯◯ Very low
Reoperation for bleeding	19 per 1000	21 per 1000 (8 to 56)	RR 1.11 (0.41 to 3.04)	744 (4 RCTs)	⊕◯◯◯ Very low
ICU length of stay (ICU LOS)		The mean ICU LOS in the intervention group was 0 (0.44 lower to 0.44 higher).			⊕◯◯◯ Very low
Hospital length of stay (H LOS)		The mean H LOS was 0.45 lower (0.9 lower to 0.01 higher).			⊕⊕◯◯ Low

*The risk in the intervention group (and its 95% CIs) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95% CI).

ORIGINAL ARTICLE

2016

Cerebral oxygen saturation and tissue hemoglobin concentration as predictive markers of early postoperative outcomes after pediatric cardiac surgery

Tomohiko Suemori[1,2], Justin Skowno[3,4], Steve Horton[5,6], Stephen Bottrell[5], Warwick Butt[7,8] & Andrew J. Davidson[1,9,10]

Hamamatsu NIRO

Table 5 Cut-off values for postoperative TOI and Δ[HHb]

	Major morbidity				Mortality			
	Sensitivity	Specificity	PPV	NPV	Sensitivity	Specificity	PPV	NPV
TOI postop <40%	21	95	27	93	25	94	12	98
TOI postop <45%	27	91	22	93	33	90	10	98
TOI postop <50%	42	83	18	94	75	83	12	99
Δ[HHb] >10	27	91	21	93	41	86	8	98
Δ[HHb] >8	33	87	18	94	50	77	6	98
Δ[HHb] >6	52	78	18	95	50	71	5	98

TOI, tissue oxygenation index; Δ[HHb], amount change in deoxygenated hemoglobin; PPV, positive predictive value; NPV, negative predictive value.

Perioperative Near-Infrared Spectroscopy Monitoring in Neonates With Congenital Heart Disease: Relationship of Cerebral Tissue Oxygenation Index Variability With Neurodevelopmental Outcome PCCM 2016

Michael C. Spaeder, MD[1]; Darren Klugman, MD[2]; Kami Skurow-Todd, MSN[3]; Penny Glass, PhD[4]; Richard A. Jonas, MD[5]; Mary T. Donofrio, MD[3]

TABLE 2. Patient and Clinical Characteristics Stratified by Neurodevelopmental Outcome

Characteristic	Normal Neurodevelopmental Outcome ($n = 24$) n (%)	Poor Neurodevelopmental Outcome ($n = 20$) n (%)	p
Age (d)	6 (IQR, 3–7)	6 (IQR, 4–9)	0.27
Weight (g)	3,482 (SD, 475)	3,320 (SD, 495)	0.14
Cardiopulmonary bypass time (min)	123 (IQR, 109–143)	116 (IQR, 106–125)	0.36
Underwent DHCA	24 (100%)	18 (90%)	0.20
DHCA time (min)	25 (IQR, 8–42)	45 (IQR, 39–50)	**0.01**
CHD classification			0.06
Class 1	12 (50%)	4 (20%)	
Class 2	2 (8%)	1 (5%)	
Class 3	0	0	
Class 4	10 (42%)	15 (75%)	
Single ventricle defects (class 3 and 4)	10 (42%)	15 (80%)	**0.03**
CHD with aortic obstruction (class 2 and 4)	12 (50%)	16 (80%)	**0.04**
Mean intraoperative cTOI	63 (SD, 7)	63 (SD, 9)	0.41
Nadir intraoperative cTOI	35 (SD, 14)	33 (SD, 16)	0.31
Intraoperative cTOI variability	2.7 (IQR, 2.2–3.5)	2.7 (IQR, 2.1–3.9)	0.99
Mean postoperative cTOI	56 (SD, 12)	55 (SD, 11)	0.32
Nadir postoperative cTOI	34 (SD, 16)	38 (SD, 11)	0.71
Postoperative cTOI variability	1.6 (IQR, 1.2–3)	1 (IQR, 0.8–1.7)	**0.01**

cTOI = cerebral tissue oxygenation index, CHD = congenital heart disease, DHCA = deep hypothermic circulatory arrest, IQR = interquartile range.
Boldface values reflect significant results.

Review Article

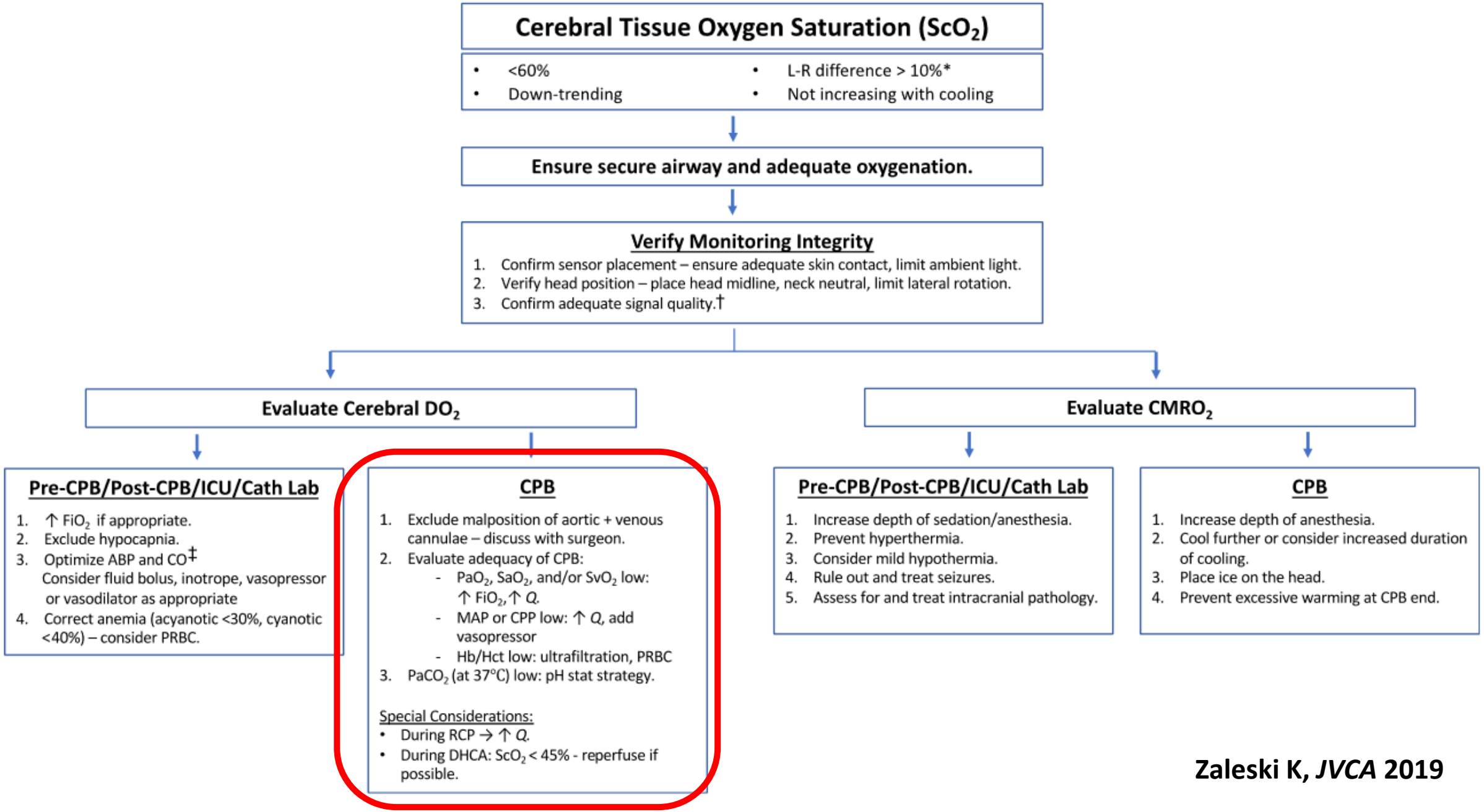
Near-Infrared Spectroscopy in Pediatric Congenital Heart Disease

Katherine L. Zaleski, MD[1], Barry D. Kussman, MBBCh, FFA(SA)

Department of Anesthesiology, Perioperative, and Critical Care Medicine, Division of Cardiac Anesthesia, Boston Children's Hospital, Boston, MA

NIRS en chirurgie cardiaque pédiatrique:

- Un outil devenu incontournale
- Algorithme interventionnel « de bon sens »
- Association pronostique modeste
- Aucune étude rapportant la faisabilité d'intervention basées sur l'utilisation du NIRS
- Prédiction d'évènements neurologiques: bas débit (et non: stroke!)



Zaleski K, *JVCA* 2019

Plan

- Introduction: conséquences neurologiques de la CEC
- Débit Sanguin cérébral
- Autorégulation cérébrale pendant la CEC
  - Théorie
  - Mesure non invasive, Cox
  - Résultats préliminaires en pédiatrie
- Autres éléments du neuromonitoring per CEC
- Conclusion

Débit Sanguin Cérébral

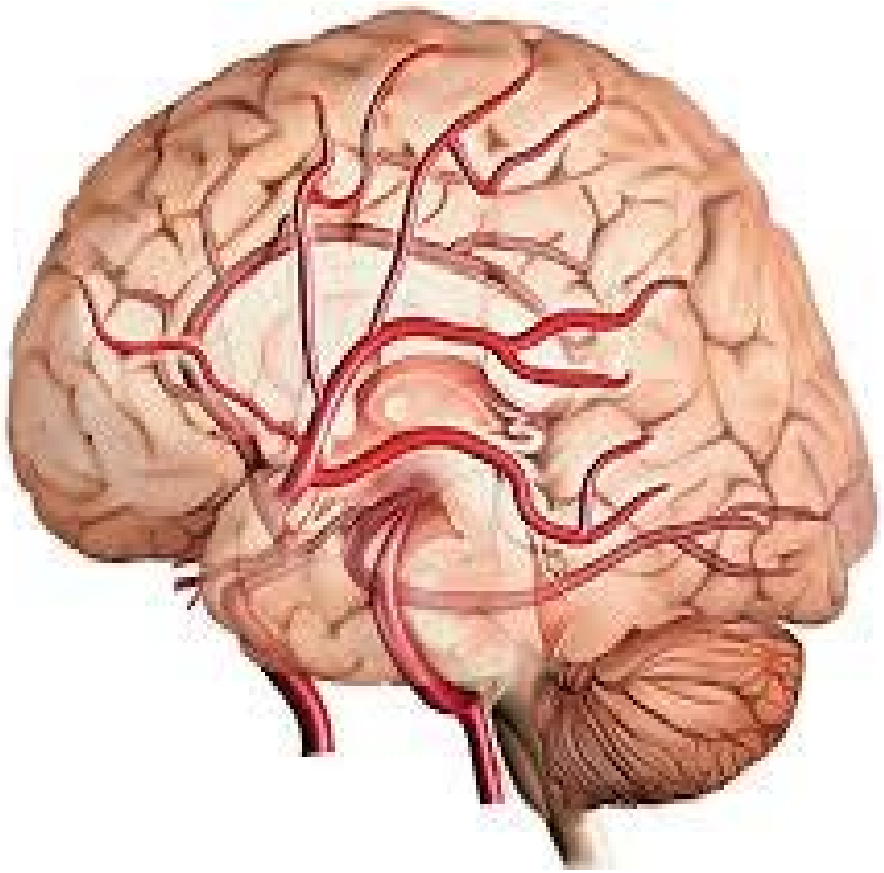
Débit Sanguin Cérébral (DSC)

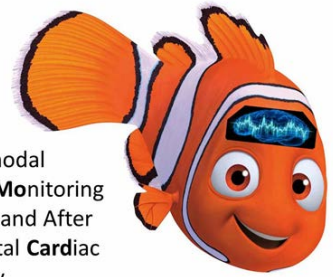
→ Seule source d'O2
→ 15 à 30% de Qc (50 ml/100g/min)

→ DSC = PPC / RVC

→ PPC = PAM – (PVC + PIC)

→ Sujet à une AUTOREGULATION

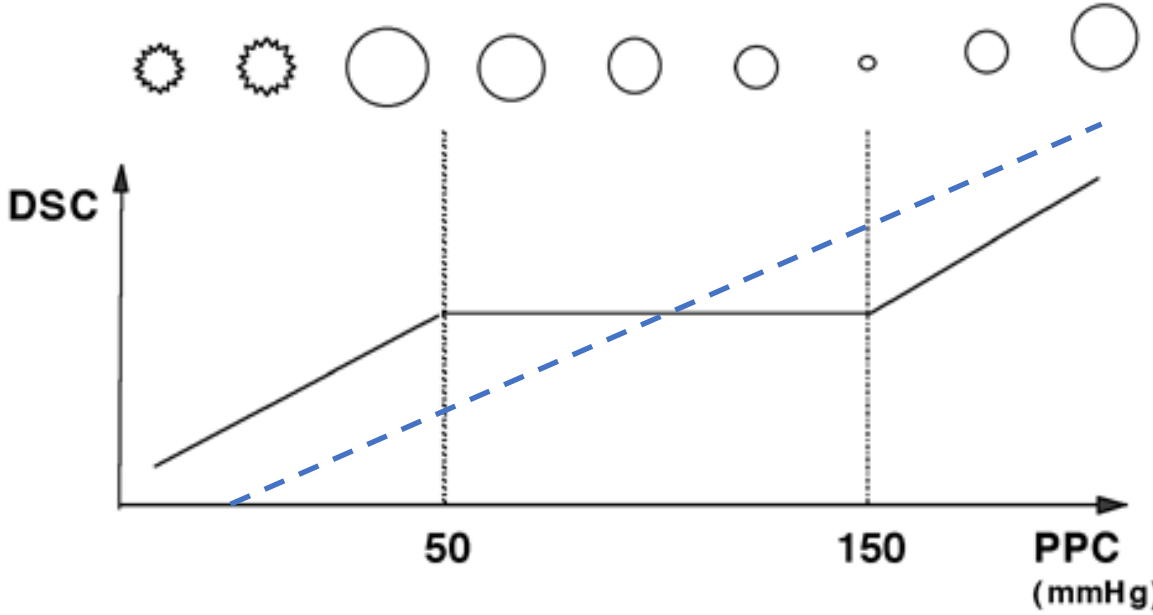




Multimodal **Ne**uro**Mo**nitoring during and After Neonatal **Card**iac Surgery

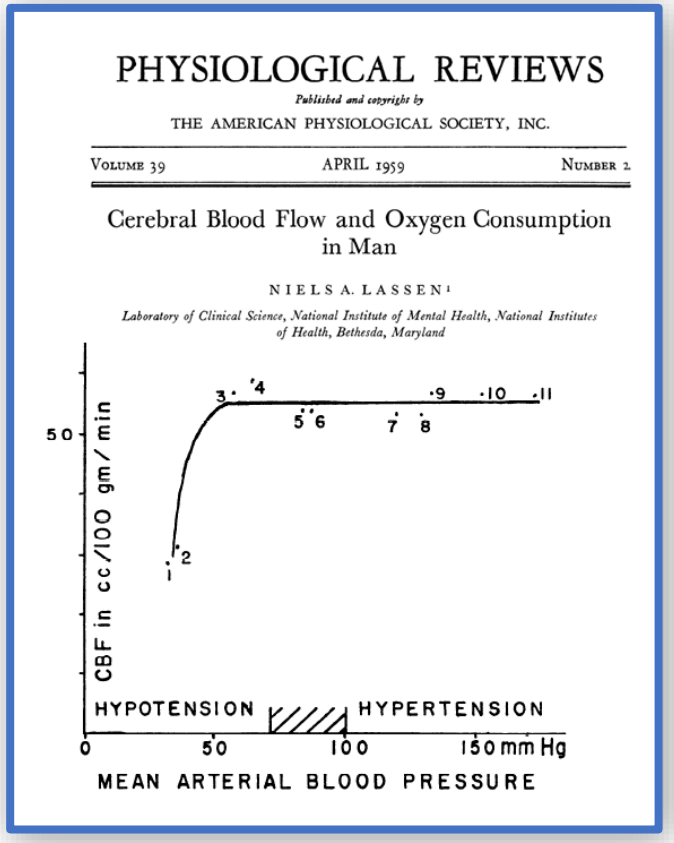
Remember your classics!

Cerebral Autoregulation (CAR): classical view



Dotted line…effect of CAR disruption

>Des travaux de Laassen à une conception dynamique de L'ARC



PHYSIOLOGICAL REVIEWS

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VOLUME 39 APRIL 1959 NUMBER 2

Cerebral Blood Flow and Oxygen Consumption in Man

NIELS A. LASSEN[1]

Laboratory of Clinical Science, National Institute of Mental Health, National Institutes of Health, Bethesda, Maryland

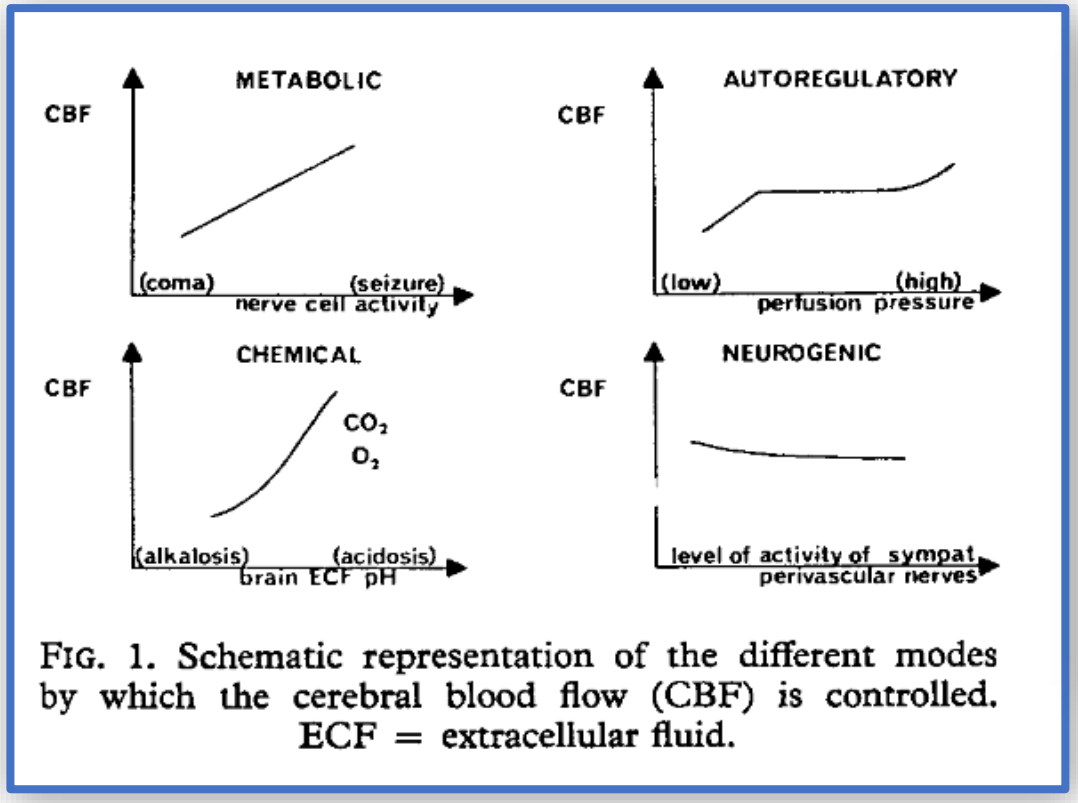
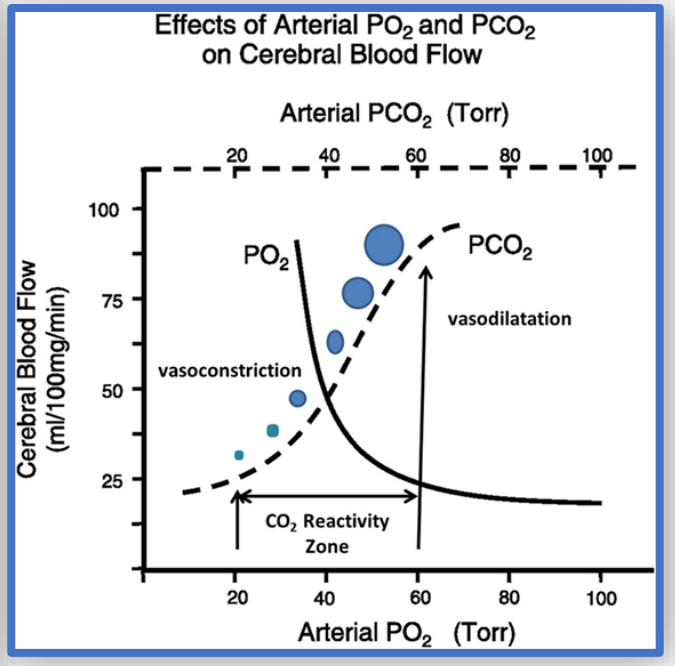
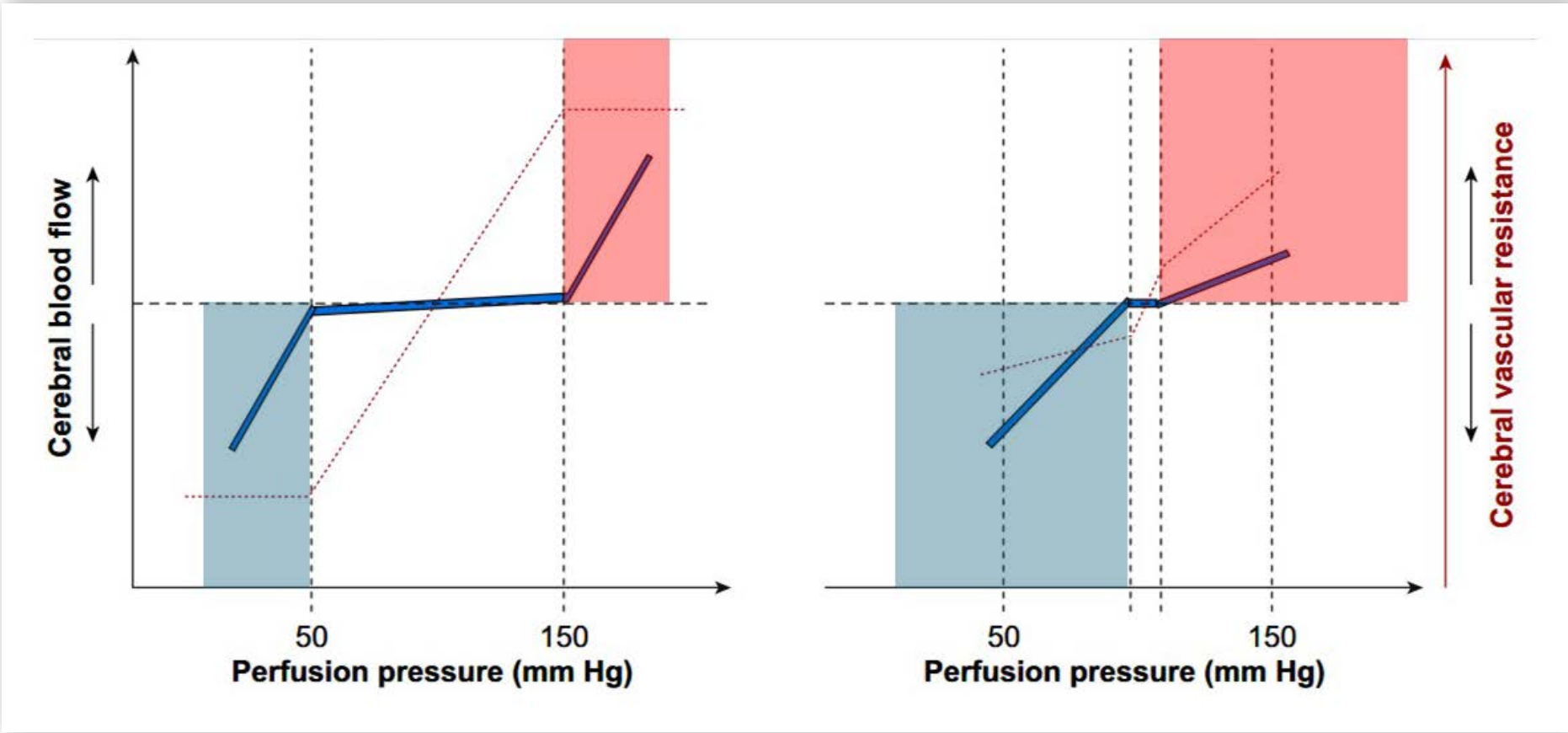


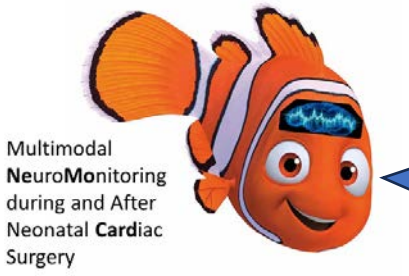
FIG. 1. Schematic representation of the different modes by which the cerebral blood flow (CBF) is controlled. ECF = extracellular fluid.



> Conséquences cliniques (‘*CAR disruption*’)

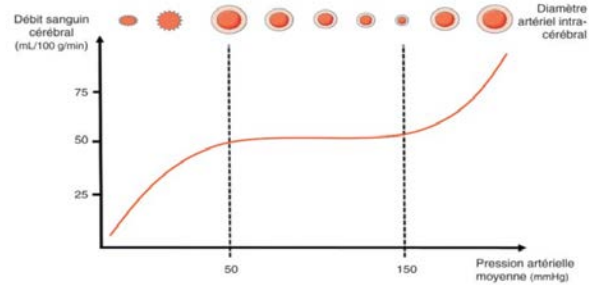


E. Vu et al, 2023



Multimodal **NeuroMo**nitoring during and After Neonatal **Cardi**ac Surgery

Comment estimer un statut d'ARC?



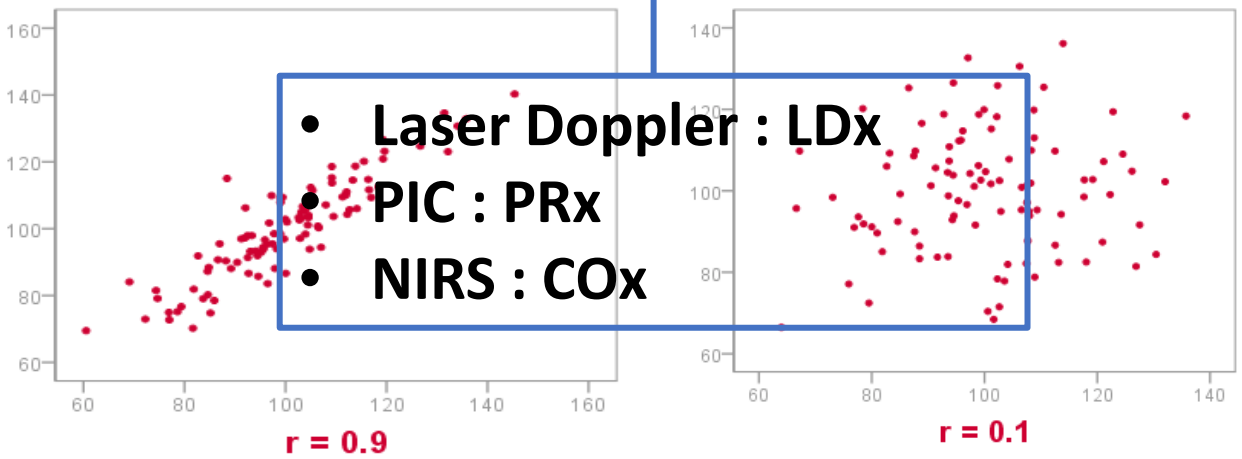
Mesurer la PAM

Estimer le DSC

- **Laser Doppler**
- **PIC**
- **NIRS**

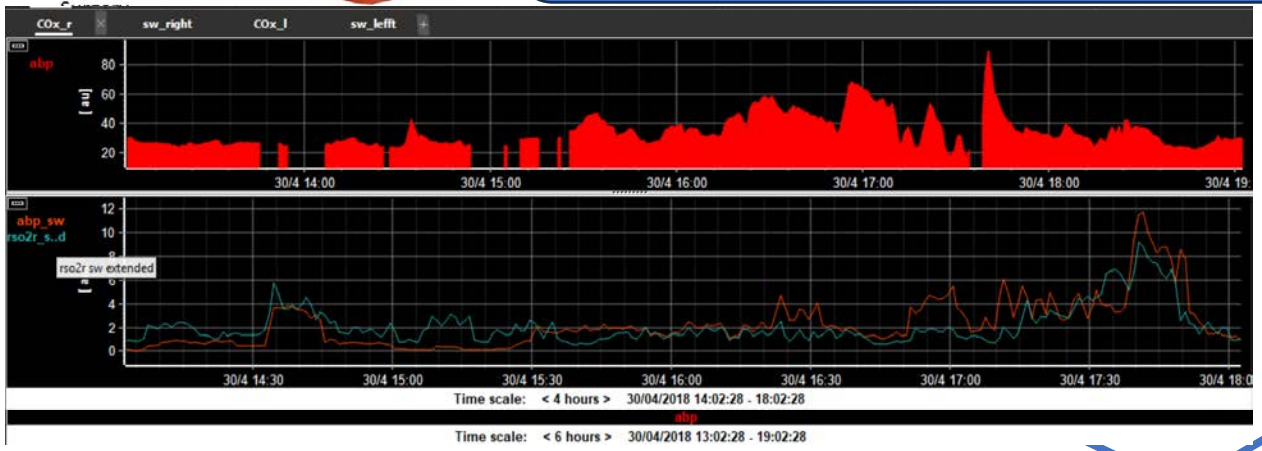
Coefficient de Corrélation

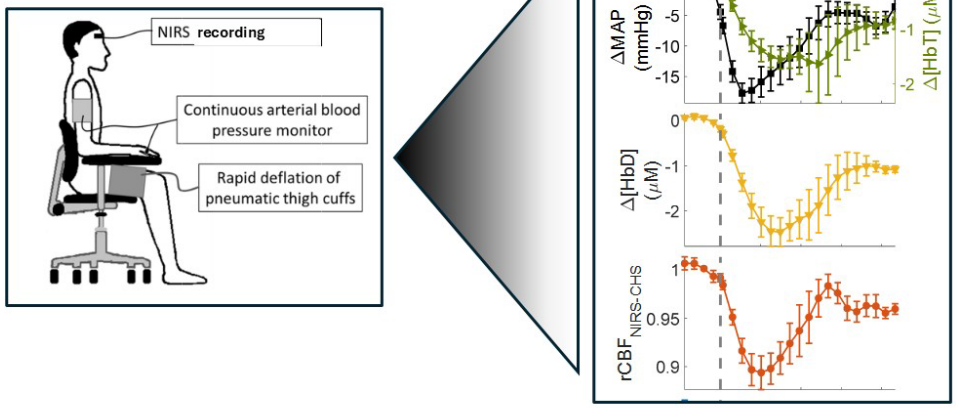
- **Laser Doppler : LDx**
- **PIC : PRx**
- **NIRS : COx**



Multimodal **NeuroMo**nitoring during and After Neonatal **Cardi**ac

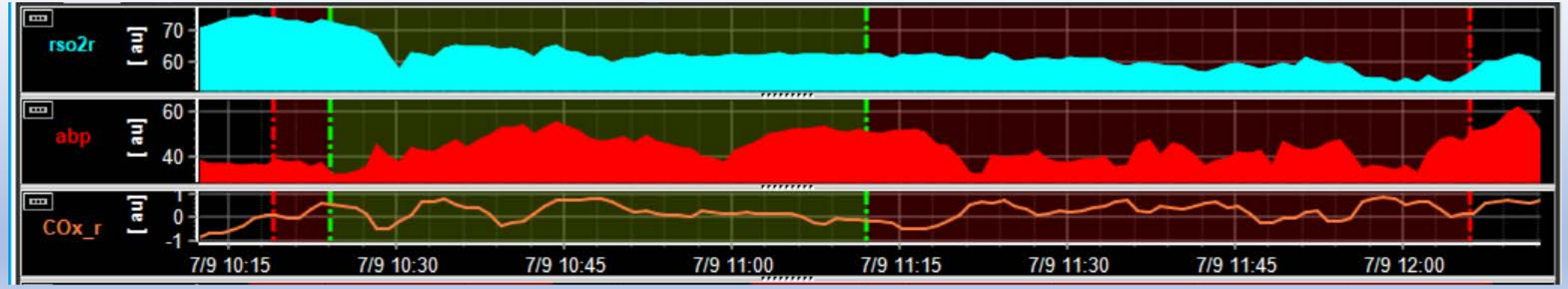
‘Frequency-based’ analysis

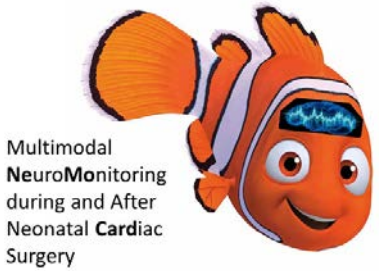




Coefficient de Corrélation: COx

Moving Correlation Factor (300sec/10sec)





Multimodal **NeuroMo**nitoring during and After Neonatal **Card**iac Surgery

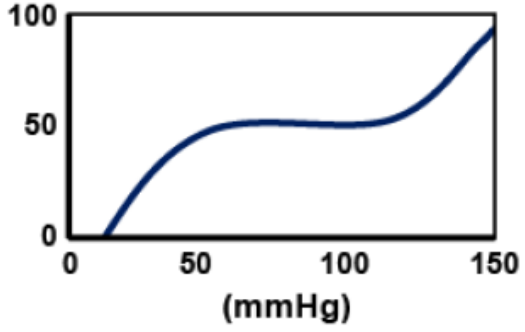
'Hybrid Model'

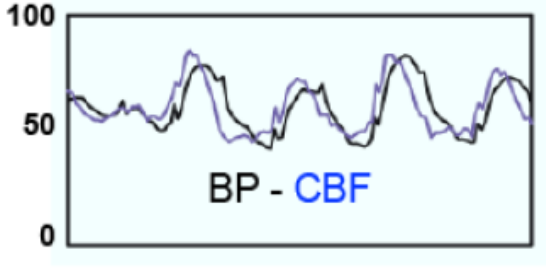
Static

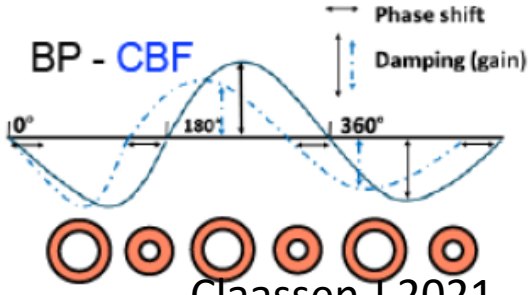
Dynamic

Vascular Diameter

CBF



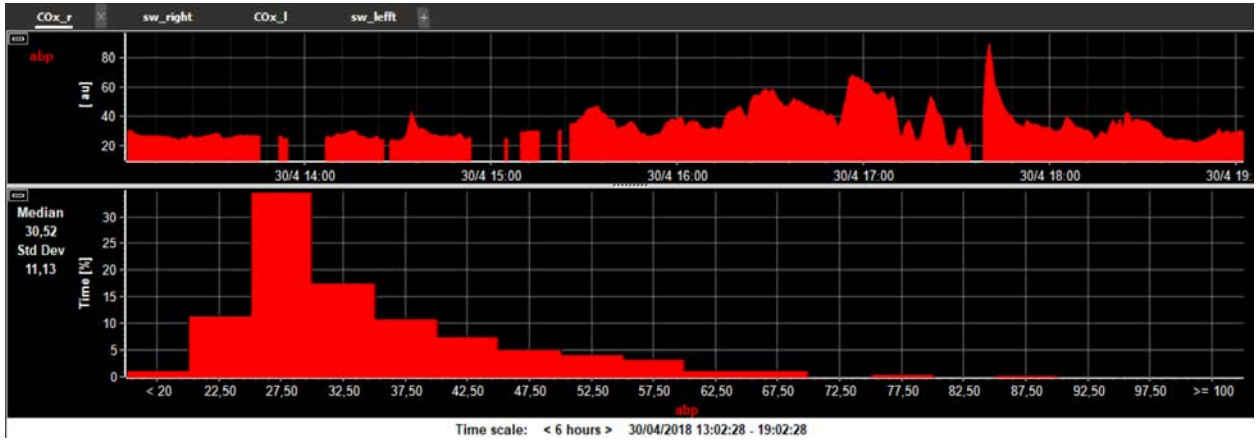




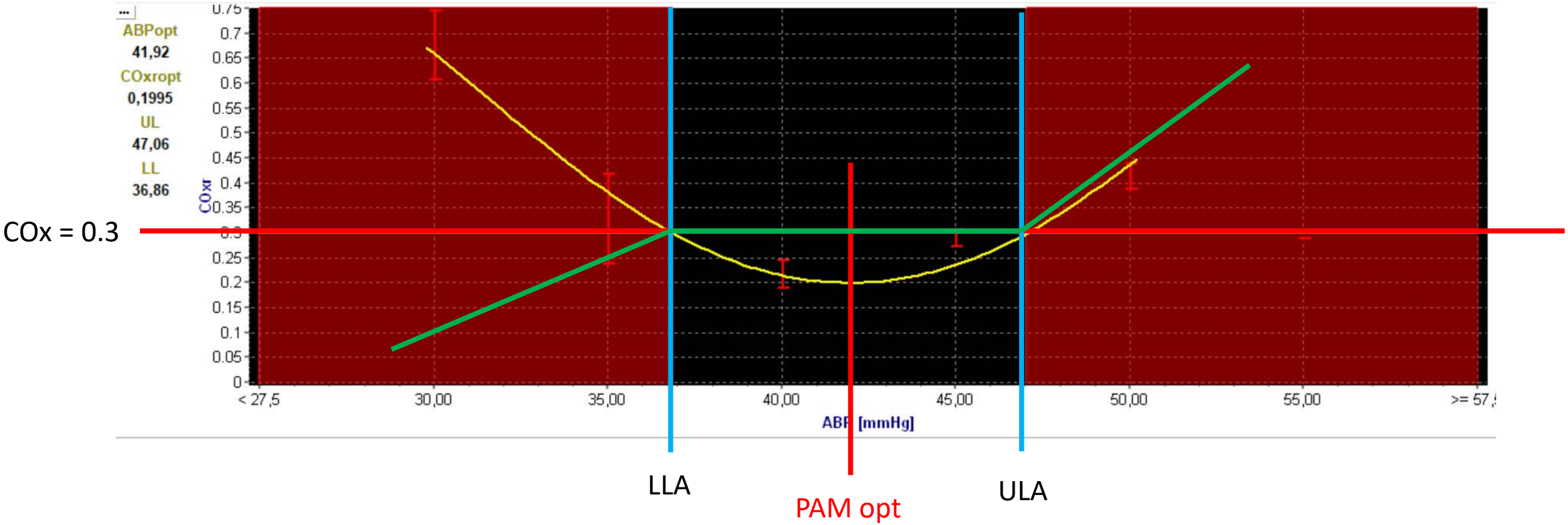
Claassen J 2021

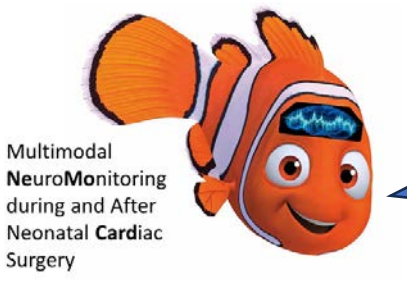
Chronicor steady state changes in BP

Rapid changes in BP



Best Fitting Curve



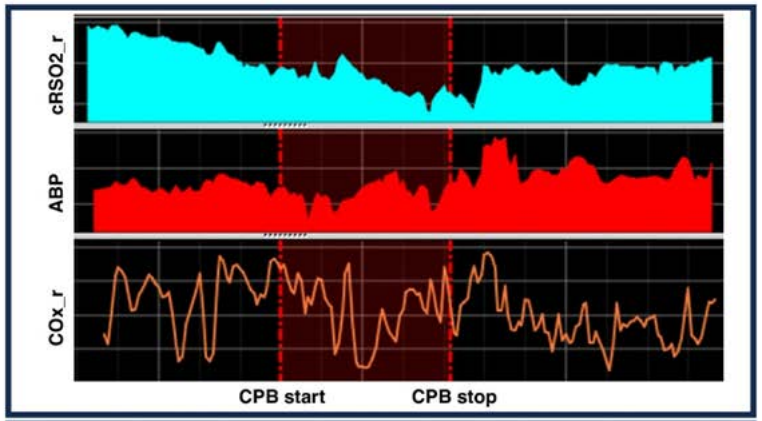


Multimodal **Neu**ro**Mo**nitoring during and After Neonatal **Card**iac Surgery

'CAR-derived metrics'

a

b



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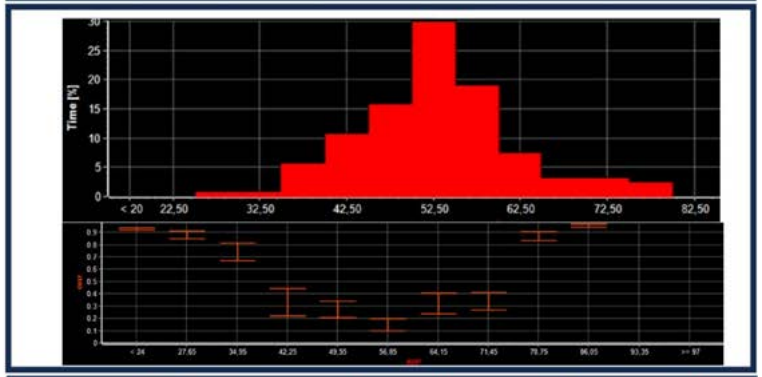

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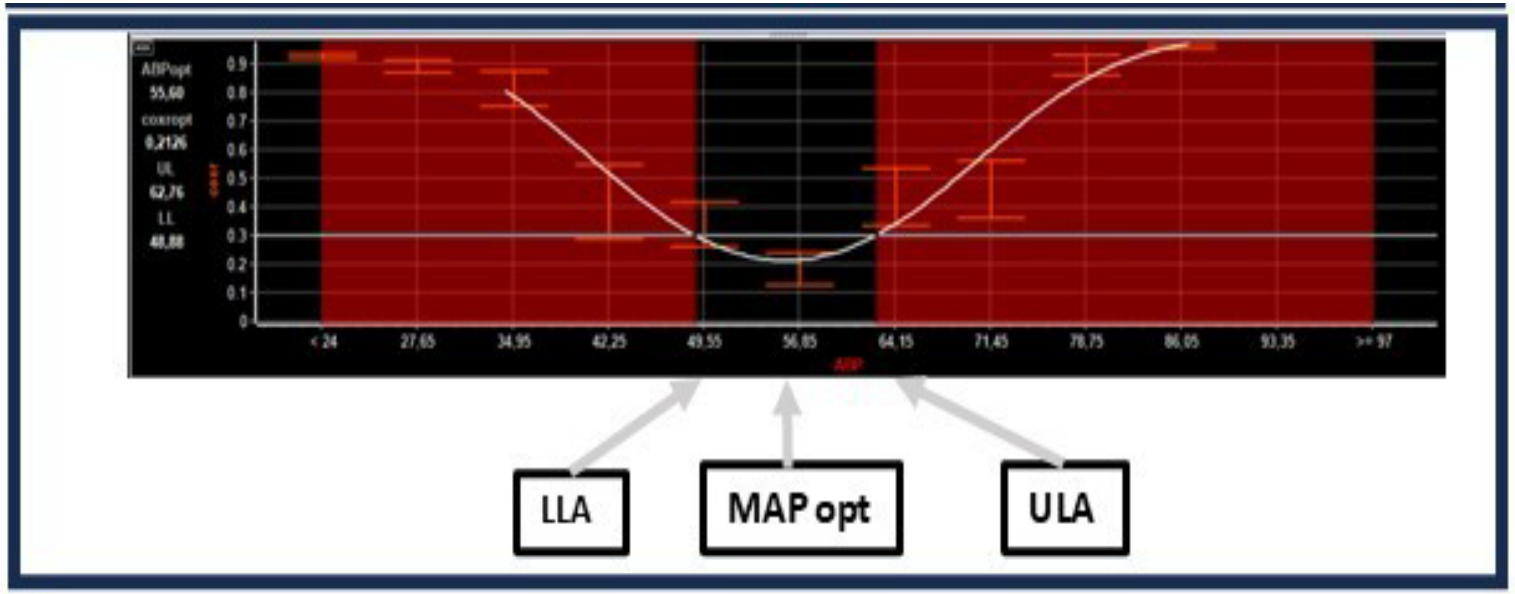
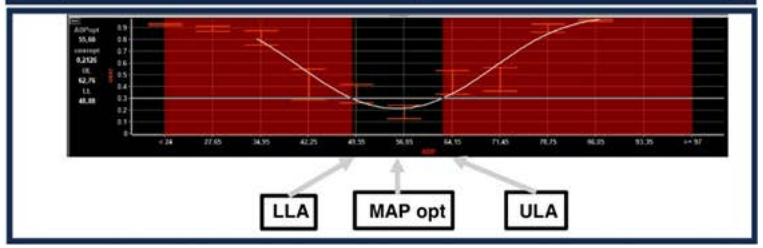
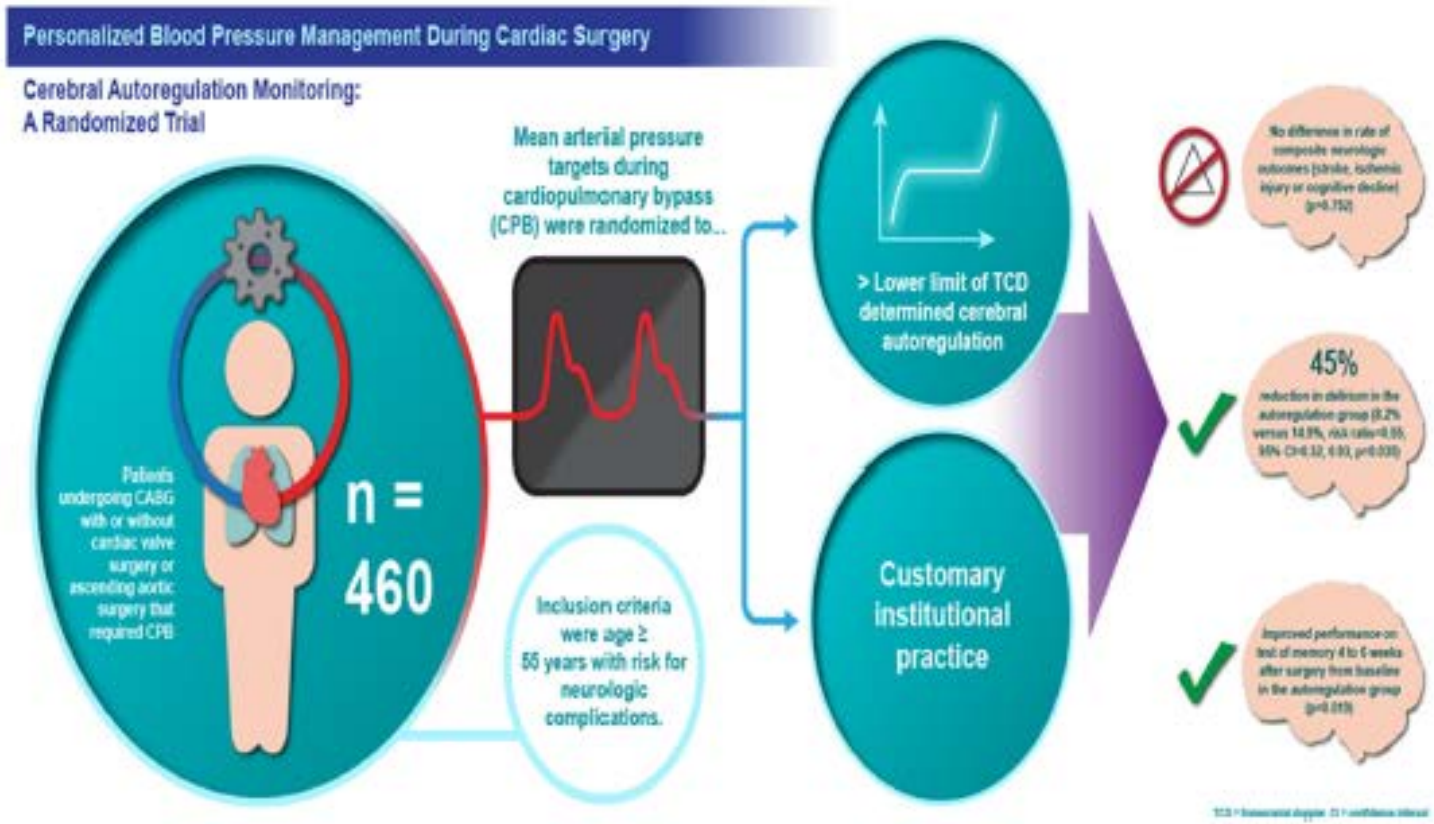




Personalized Blood Pressure Management During Cardiac Surgery With Cerebral Autoregulation Monitoring: A Randomized Trial

Charles W. Hogue, MD,[*] Charles H. Brown IV, MD, MPH,[†] Daijiro Hori, MD,[‡] Masa Ono, MD,[§] Yohei Nomura, MD,[‡] Lauren C. Balmert, PhD,[¶] Nina Srdanovic, MS,[¶] Jordan Grafman, PhD,[‖] and Kenneth Brady, MD[**] The Cerebral Autoregulation Study Group [#]



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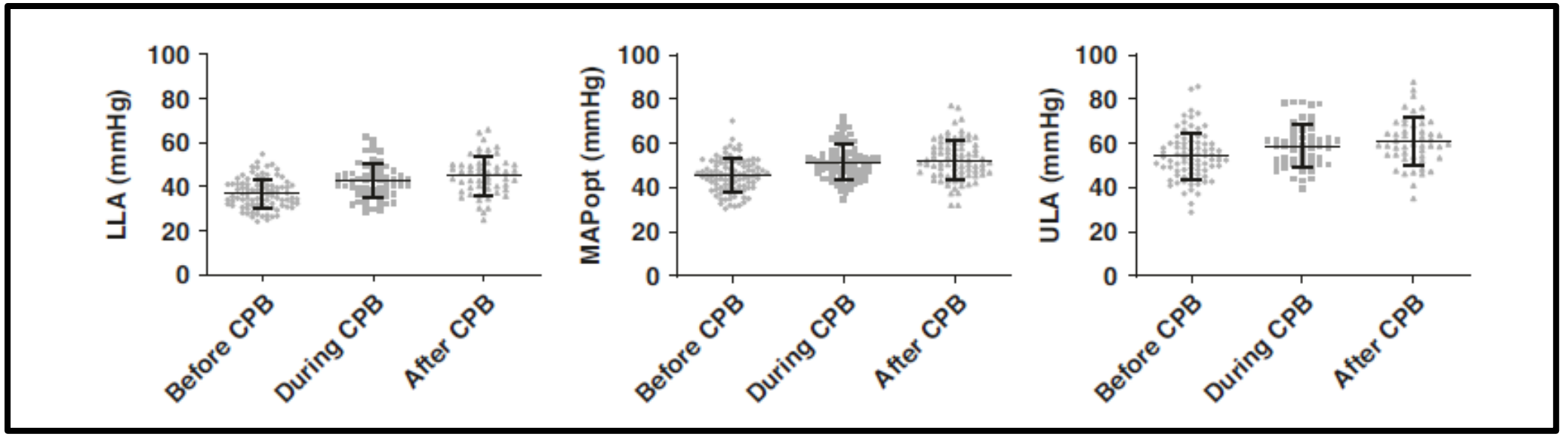
CLINICAL RESEARCH ARTICLE

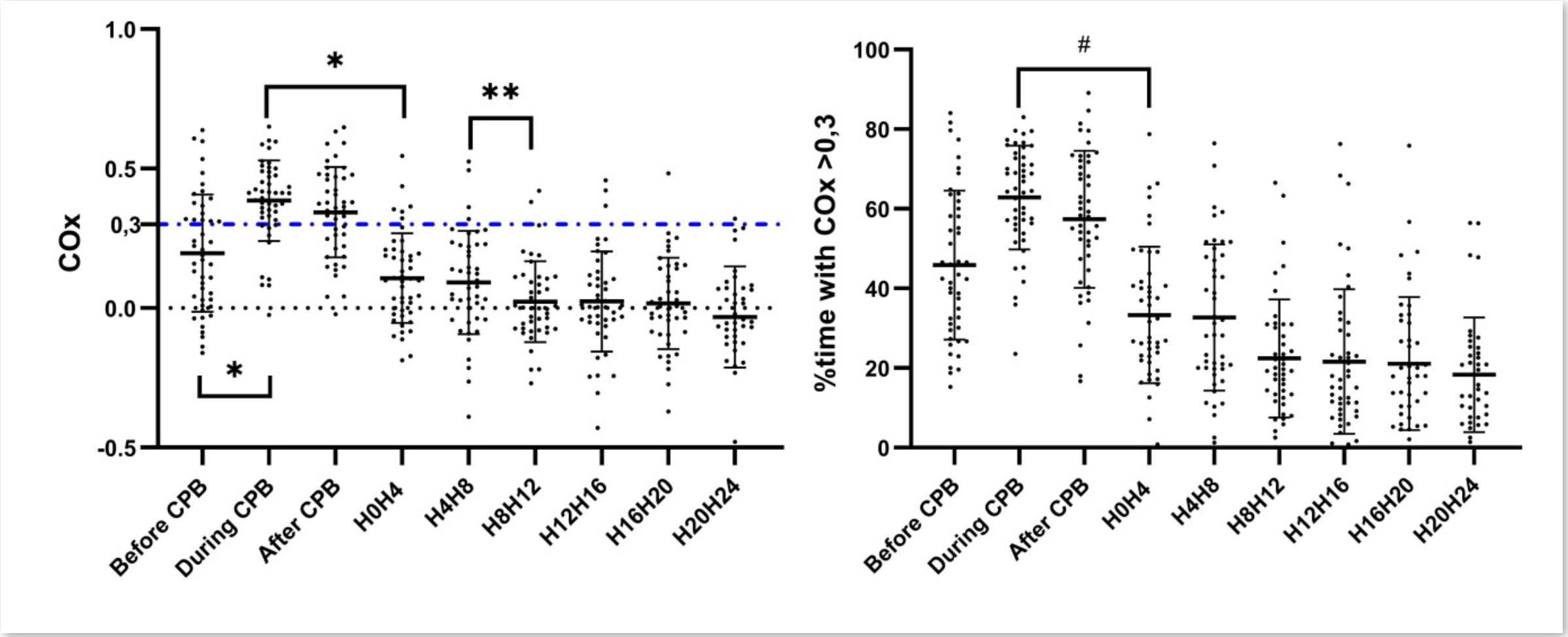
Check for updates

Clinical research study: cerebral autoregulation in neonates and infants undergoing open heart surgery: global patterns and derived cerebral hemodynamic metrics

Pierre Bourgoin[1,2,3]✉, Erta Beqiri[4], Peter Smielewski[4], Ariane De Windt[3], Remi Bernardon[3], Guillaume Emeriaud[5], Ugo Gouedard[3], Alban Baruteau[6], Alexis Chenouard[2], Nicolas Joram[2] and Pascal Amedro[1,7]

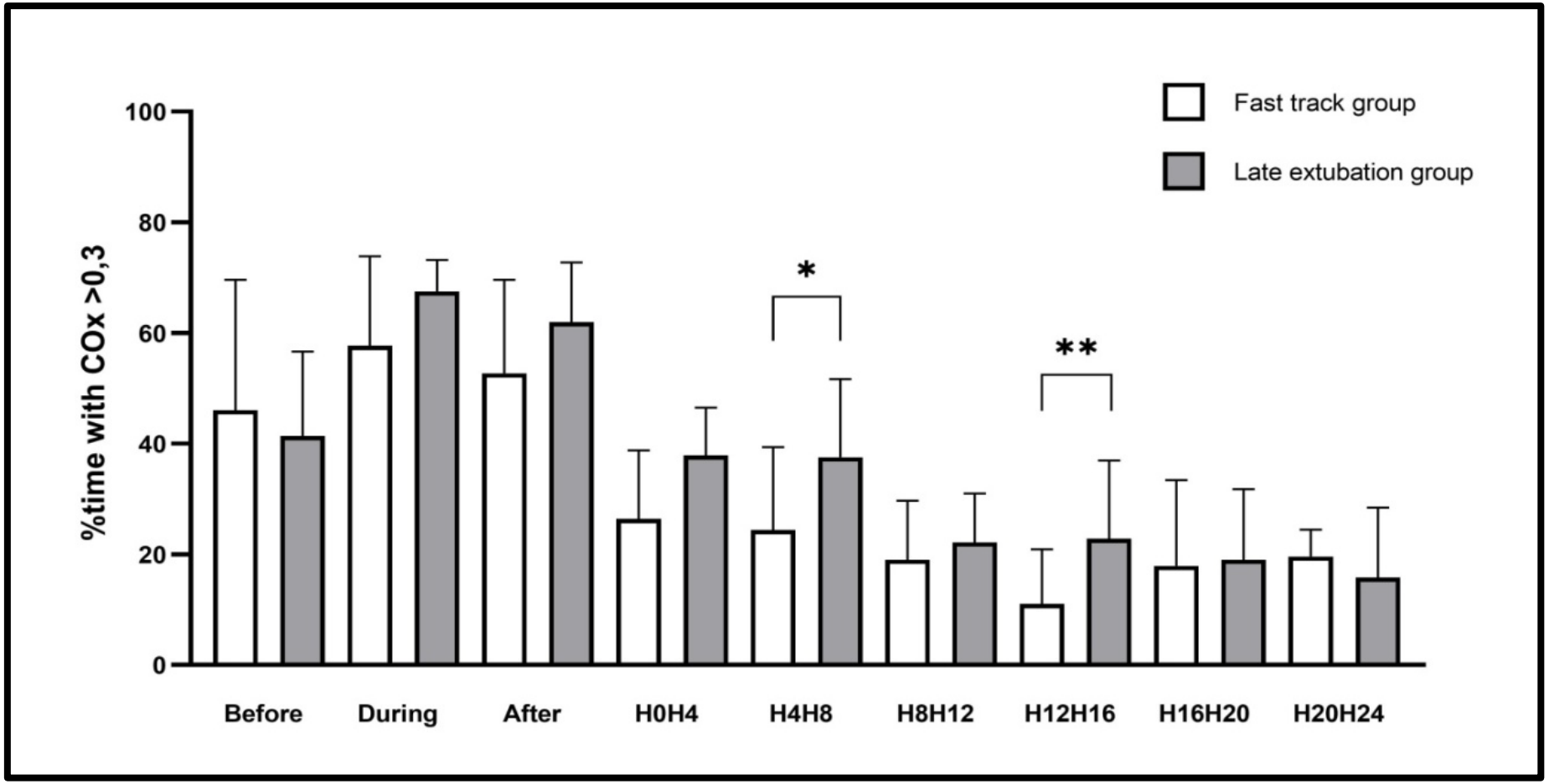


> CAR-status recovery after CPB (1)



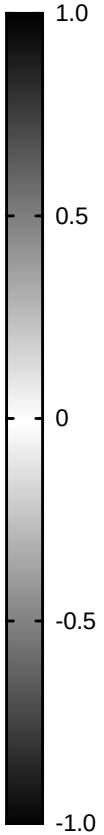
F Mette et al…2026

CAR-status recovery after CPB (2)



Body Perfusion (lactates)

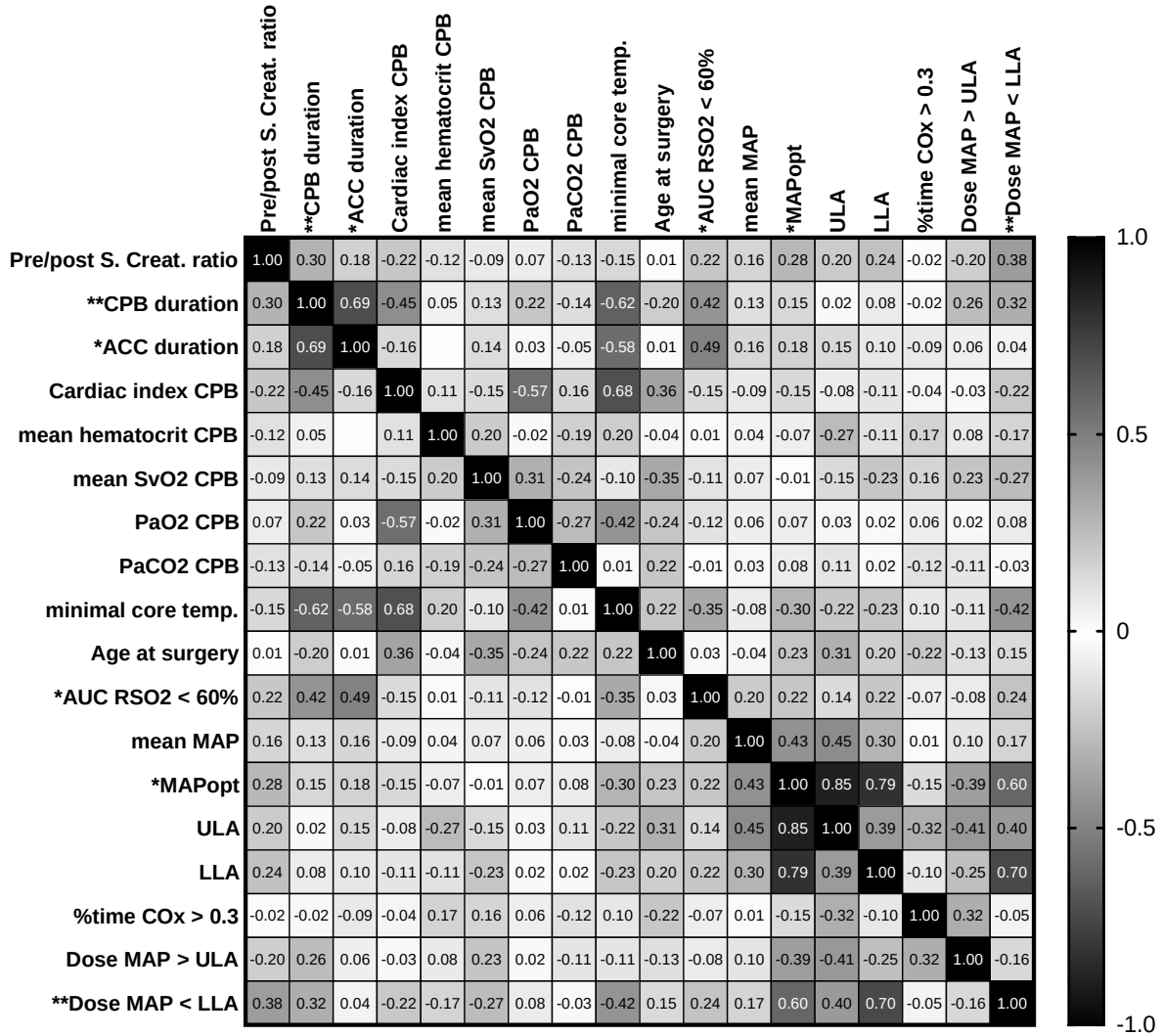
	24h max. Lactate	***CPB duration	**ACC duration	Cardiac index CPB	mean hematocrit CPB	mean SvO2 CPB	PaO2 CPB	PaCO2 CPB	minimal core temp.	Age at surgery	**AUC RSO2 < 60%	mean MAP	*MAPopt	ULA	*LLA	%time COx > 0.3	Dose MAP > ULA	***Dose MAP < LLA
24h max. Lactate	1.00	0.42	0.25	-0.34	-0.06	0.07	0.30	-0.11	-0.44	-0.03	0.26	0.13	0.26	0.29	0.25	0.02	-0.01	0.48
***CPB duration**	0.42	1.00	0.69	-0.45	0.05	0.13	0.22	-0.14	-0.62	-0.20	0.42	0.13	0.15	0.02	0.08	-0.02	0.26	0.32
ACC duration	0.25	0.69	1.00	-0.16		0.14	0.03	-0.05	-0.58	0.01	0.49	0.16	0.18	0.15	0.10	-0.09	0.06	0.04
Cardiac index CPB	-0.34	-0.45	-0.16	1.00	0.11	-0.15	-0.57	0.16	0.68	0.36	-0.15	-0.09	-0.15	-0.08	-0.11	-0.04	-0.03	-0.22
mean hematocrit CPB	-0.06	0.05		0.11	1.00	0.20	-0.02	-0.19	0.20	-0.04	0.01	0.04	-0.07	-0.27	-0.11	0.17	0.08	-0.17
mean SvO2 CPB	0.07	0.13	0.14	-0.15	0.20	1.00	0.31	-0.24	-0.10	-0.35	-0.11	0.07	-0.01	-0.15	-0.23	0.16	0.23	-0.27
PaO2 CPB	0.30	0.22	0.03	-0.57	-0.02	0.31	1.00	-0.27	-0.42	-0.24	-0.12	0.06	0.07	0.03	0.02	0.06	0.02	0.08
PaCO2 CPB	-0.11	-0.14	-0.05	0.16	-0.19	-0.24	-0.27	1.00	0.01	0.22	-0.01	0.03	0.08	0.11	0.02	-0.12	-0.11	-0.03
minimal core temp.	-0.44	-0.62	-0.58	0.68	0.20	-0.10	-0.42	0.01	1.00	0.22	-0.35	-0.08	-0.30	-0.22	-0.23	0.10	-0.11	-0.42
Age at surgery	-0.03	-0.20	0.01	0.36	-0.04	-0.35	-0.24	0.22	0.22	1.00	0.03	-0.04	0.23	0.31	0.20	-0.22	-0.13	0.15
****AUC RSO2 < 60%**	0.26	0.42	0.49	-0.15	0.01	-0.11	-0.12	-0.01	-0.35	0.03	1.00	0.20	0.22	0.14	0.22	-0.07	-0.08	0.24
mean MAP	0.13	0.13	0.16	-0.09	0.04	0.07	0.06	0.03	-0.08	-0.04	0.20	1.00	0.43	0.45	0.30	0.01	0.10	0.17
***MAPopt**	0.26	0.15	0.18	-0.15	-0.07	-0.01	0.07	0.08	-0.30	0.23	0.22	0.43	1.00	0.85	0.79	-0.15	-0.39	0.60
ULA	0.29	0.02	0.15	-0.08	-0.27	-0.15	0.03	0.11	-0.22	0.31	0.14	0.45	0.85	1.00	0.39	-0.32	-0.41	0.40
***LLA**	0.25	0.08	0.10	-0.11	-0.11	-0.23	0.02	0.02	-0.23	0.20	0.22	0.30	0.79	0.39	1.00	-0.10	-0.25	0.70
%time COx > 0.3	0.02	-0.02	-0.09	-0.04	0.17	0.16	0.06	-0.12	0.10	-0.22	-0.07	0.01	-0.15	-0.32	-0.10	1.00	0.32	-0.05
Dose MAP > ULA	-0.01	0.26	0.06	-0.03	0.08	0.23	0.02	-0.11	-0.11	-0.13	-0.08	0.10	-0.39	-0.41	-0.25	0.32	1.00	-0.16
***Dose MAP < LLA**	0.48	0.32	0.04	-0.22	-0.17	-0.27	0.08	-0.03	-0.42	0.15	0.24	0.17	0.60	0.40	0.70	-0.05	-0.16	1.00



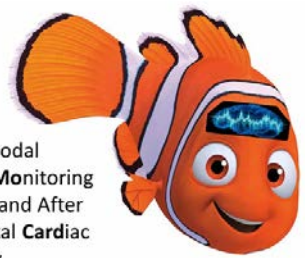
	Coefficient	95% CI	p-value	Sig.
(Intercept)	4.09	[-1.874, 10.048]		
CPB duration	0.004	[-0.008, 0.017]	0.52	
RACHS-2 category	0.213	[-0.768, 1.192]	0.66	
Dose MAP < LLA	0.227	[0.081, 0.371]	0.003	**
AUC RSO2 < 60%	0.036	[-0.001, 0.073]	0.06	
Cardiac Index [l/min/m²]	-1.302	[-3.478, 0.872]	0.23	

Body Perfusion (reins)

	Coefficient	95% CI	p-value	Sig.
(Intercept)	0.56	[0.18, 0.94]		
CPB duration	0.003	[0.0002, 0.005]	0.03	*
RACHS-2 category	-0.015	[-0.18, 0.16]	0.86	
Dose MAP < LLA	0.032	[0.003, 0.06]	0.03	*
AUC RSO2 < 60%	0.0006	[-0.006, 0.008]	0.85	
Cardiac Index [l/min/m²]	-0.06	[-0.54, 0.42]	0.78	



Et le cerveau?



Multimodal
Neuro**Mo**nitoring
during and After
Neonatal **Card**iac
Surgery

Original Article

Optimal brain perfusion pressure derived from the continuous monitoring of cerebral autoregulation status during neonatal heart surgery under cardiopulmonary bypass in relation to brain injury: An observational study

Pierre Bourgoin [a,b,c,*], Erta Beqiri [d], Peter Smielewski [d], Alexis Chenouard [b], Aurélie Gaultier [e], Flavie Sadones [f], Ugo Gouedard [c], Nicolas Joram [b], Pascal Amedro [a,g]

[a] *IHU Liryc, Electrophysiology and Heart Modelling Institute, INSERM 1045, University of Bordeaux, Pessac, France*
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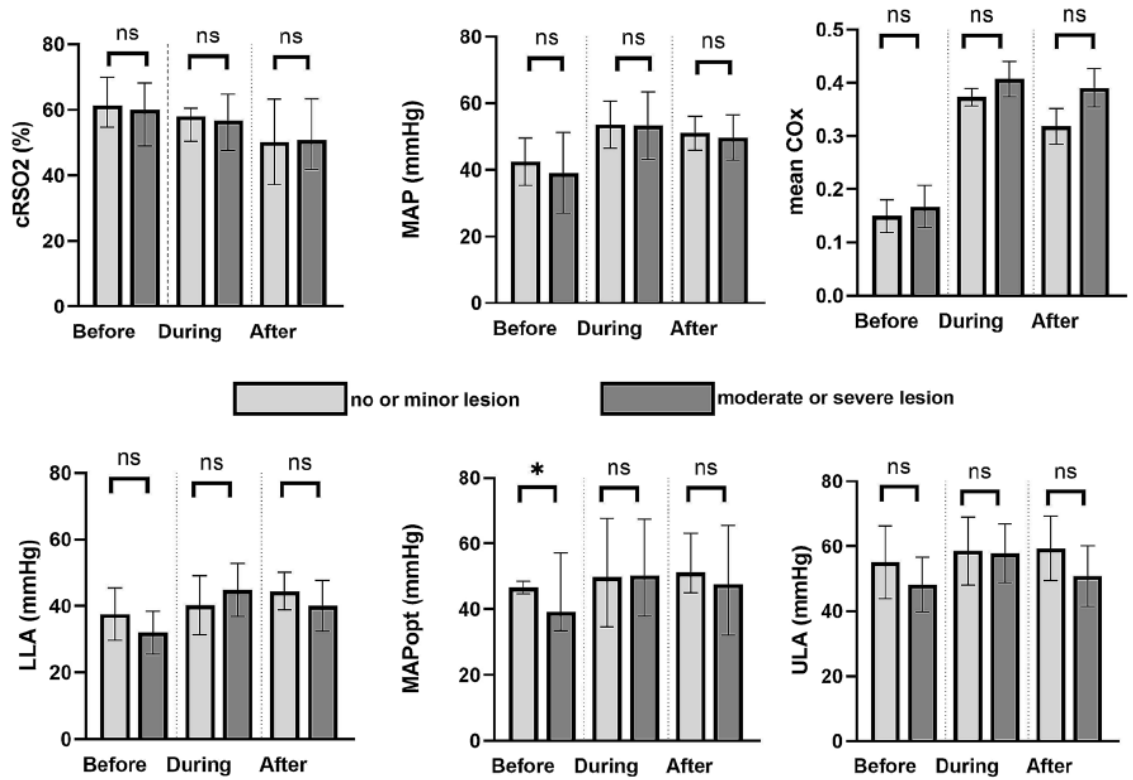
[d] *Brain Physics Laboratory, Department of Clinical Neurosciences, University of Cambridge, Cambridge, United Kingdom*
[e] *Department of Biostatistics, Nantes University, Nantes, France*
[f] *Department of Pediatric Radiology, Nantes University Hospital, Nantes, France*
[g] *Pediatric and Congenital Cardiology Department, M3C National Reference Center, Bordeaux University Hospital, Bordeaux, France*

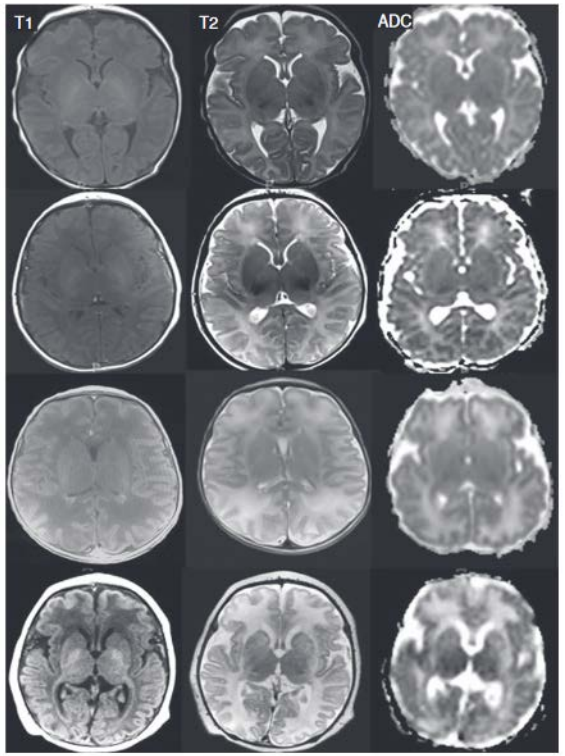
52 neonates operated under CPB during the study period (March 2020- Jan 2022)

12 did not undergo MRI examination before hospital discharge AND/OR had unsuccesfull monitoring throughout ICM+ software

1 presented post operative cardiac arrest and ECMO
1 died before MRI examination completion

38 patients with post operative MRI retained for analysis
- ✓ 21 presented no or minimal lesion
- ✓ 17 presented post operative MRI injury score ≥2





	Total	No or 1 Minor lesion	Moderate or severe lesion
	(n = 38)	(n = 21)	(n = 17)
White Mater Injury (WMI)			
0: No WMI lesion	35 (92.11%)	21 (100.00%)	14 (82.35%)
1: Less than 3 lesions of less than 2 mm each or less than 5 mm diameter total lesion	0		
2: more than 3 WMI lesions OR one lesion> 2 mm, OR total diameter > 5mm	3 (7.89%)	0 (0.00%)	3 (17.65%)
3: severe: > 15 mm total diameter	0		
Ischemic stroke			
0 : No ischemic stroke	33 (86.84%)	20 (95.24%)	13 (76.47%)
1: less than 1/3 of an arterial territory OR ischemic zone less than 5mm	3 (7.89%)	1 (4.76%)	2 (11.76%)
2: 1/3 to 2/3 of an arterial territory OR ischemic zone diameter 6 to 15 mm	1 (2.63%)	0 (0.00%)	1 (5.88%)
3: > 2/3 of an arterial territory OR total ischemic zone > 15 mm	1 (2.63%)	0 (0.00%)	1 (5.88%)
Intraparenchymal hemorragic (IPH) stroke			
0: no IPH	38 (100.00%)	21 (100.00%)	17 (100.00%)
1 : IPH 1-5 mm diameter	0		
2 :IPH 6-15 mm diameter	0		
3 : IPH > 15 mm diameter	0		
Intraparenchymal punctiform lesion (bleeds)			
0: no bleed	8 (21.05%)	8 (38.10%)	0 (0.00%)
1: 1 to 3 punctiform lesions of < 2mm each	17 (44.74%)	12 (57.14%)	5 (29.41%)
2: 4 a 6 punctiform lesions of < 2 mm each	10 (26.32%)	0 (0.00%)	10 (52.94%)
3: > 6 lesions de < 2 mm each	3 (7.89%)	0 (0.00%)	3 (17.65%)
Intraventricular hemorrage (IVH)			
0: no IVH	34 (89.47%)	20 (95.24%)	14 (82.35%)
1 :IVH < 6 mm diameter	3 (7.89%)	1 (4.76%)	2 (11.76%)
2: IVH-isolated OR total diameter 6 to 15 mm	1 (2.63%)	0 (0.00%)	1 (5.88%)
3: IVH and Intraventricular dilatation OR total diameter > 15 mm	0		
Subdural Hemorrage (SDH)			
0: no SDH or isolated posterior SDH evocating perinatal SDH	33 (86.84%)	19 (90.48%)	14 (82.35%)
1: Minimal sus tentorial SDH	5 (13.16%)	2 (9.52%)	3 (17.65%)
2 : Spread to interhemispheric fissure in occipital aera	0		
3 : Larger hemorrage, interhemispheric to parietal or frontal aera	0		
Cerebral Venous Thrombosis (CVT)			
0: No CVT	36 (94.74%)	21 (100.00%)	15 (88.24%)
1: CVT, one transverse sinus	2 (5.26%)	0 (0.00%)	2 (11.76%)
2 :CVT, bilateral	0		
3 :CVT, bilateral AND sagittal	0		

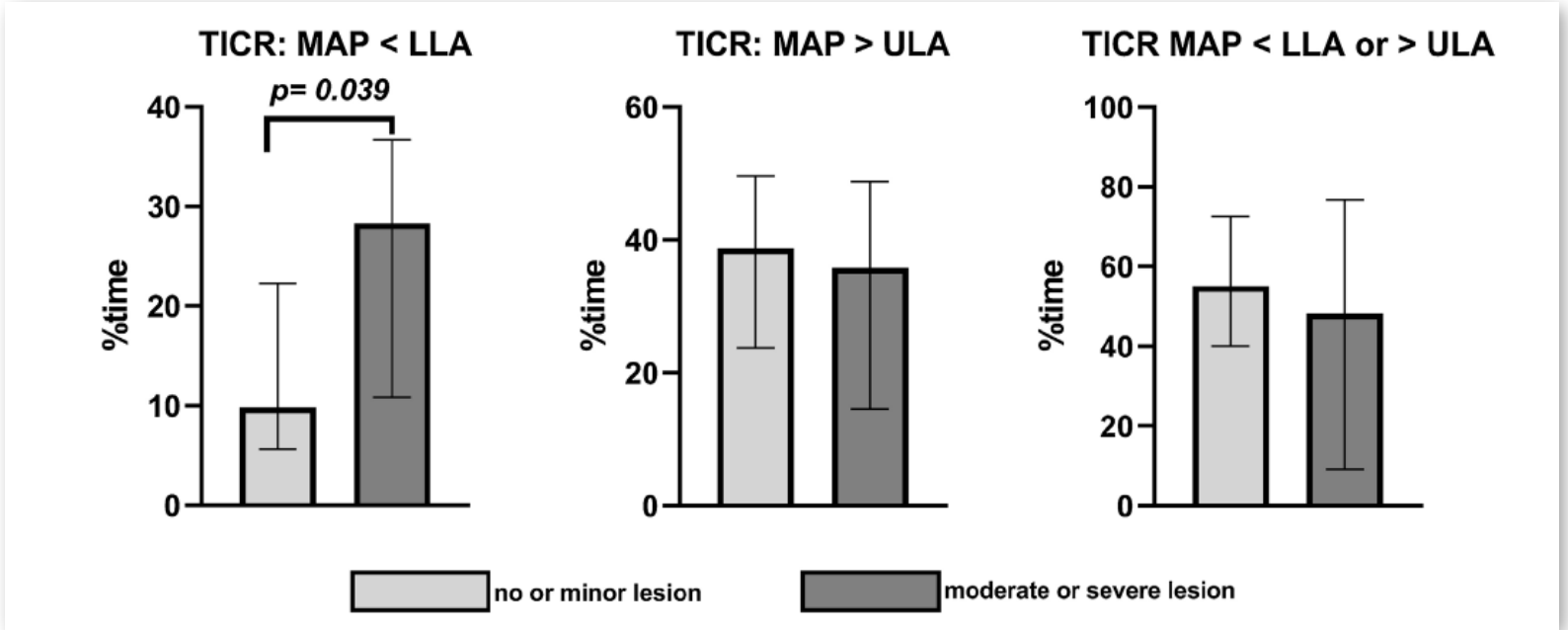


Table 2
Hemodynamic and metrics derived from the monitoring of CAR during CPB according to post-operative MRI findings.

Variable	All patients (n = 38)	No or minor lesion (n = 21)	Moderate or severe lesion (n = 17)	*p*-Value
MAP, mean values (mmHg)	53.5 ± 8.3	53.6 ± 7.0	53.2 ± 10.2	0.91
%Time MAP < 40 mmHg (%)	14.8 [9.3–24.5]	13.2 [8.3–23.4]	14.9 [11.2–27]	0.80
$cRSO_2$, mean values (%)	56.6 ± 9.7	55.8 ± 9.3	57.7 ± 10.7	0.59
Dose $cRSO_2$ < 60% (%*h)	13.3 [5.6–32.5]	14.6 [5.1–28.0]	10.9 [7.5–35.6]	0.39
Dose $cRSO_2$ < 50% (%*h)	2.6 [0.14–10.5]	2.4 [0.1–11.7]	2.9 [0.2–10.9]	0.92
Dose $cRSO_2$ < 40% (%*h)	0.4 [0.0–2.3]	3.3 [0.0–2.9]	0.2 [0.0–1.6]	0.90
Mean COx	0.38 ± 0.09	0.37 ± 0.08	0.41 ± 0.13	0.32
Dose COx > 0.3 (unit*h)	0.67 ± 0.31	0.62 ± 0.29	0.74 ± 0.35	0.28
MAPopt (mmHg)	49.9 [46–55.9]	49.7 [44.1–55.2]	50.1 [46.4–59.4]	0.74
LLA (mmHg)	40.8 [36.8–47.2]	39.6 [33.6–41.9]	46.1 [40.0–49.4]	0.09
ULA (mmHg)	59.5 [50.1–65.7]	60.8 [49.6–65.4]	58.1 [51.1–66.6]	0.92
%Time MAP > ULA (%)	37.5 [23.8–48.0]	38.8 [26.4–49.0]	35.8 [18.2–43.8]	0.77
Dose MAP > ULA (mmHg*h)	5.7 [2.4–9.7]	8.1 [2.6–11.0]	4.2 [2.5–8.1]	0.45
%Time MAP < LLA (%)	16.7 [8.3–29.0]	9.9 [6.9–18.5]	28.3 [17.1–32.9]	**0.039**
Dose ABP < LLA[‡] (mmHg*h)	1.8 [0.7–5.9]	0.8 [0.5–3.6]	5.0 [1.5–7.0]	0.06

Perspectives (1)

Intégration d'un nouveau monitoring au bloc/ En réanimation -Etapes-

Etapes	Exemple du monitoring de l'ARC
Faisabilité dans une population d'intérêt	✓ CEC néonatale : patient à risque de lésions neurologiques
Eléments de pertinence clinique, preuve de concept	✓ Détermination de pression de perfusion optimale, temps passé en dehors d la cible, lésions viibles en imagerie
Association à un élément du devenir	✓ Association à des marqueurs de la perfusion d'organes
Détermination de seuils critiques, valeur pronostique	✗ Nécessite un plus grand nombre de patient et un critère de jugement sensible. En cours.
Validation en cohorte externe	✗ En cours
Intégration dans un algorithme décisionnel	✗ En projet
Preuve de la supériorité du management grâce à l'outil	✗ A évaluer

Plan

- Introduction: conséquences neurologiques de la CEC
- Débit Sanguin cérébral
- Autorégulation cérébrale pendant la CEC
  - Théorie
  - Mesure non invasive, Cox
  - Preuve de concept chez l'adulte
  - Résultats préliminaires en pédiatrie
- Autres éléments du neuromonitoring per CEC
- Conclusion

Review Article

Neuromonitoring Modalities in Pediatric Cardiac Anesthesia: A Review of the Literature

Elizabeth Finucane, DO[1], Edmund Jooste, MBChB,
Kelly A. Machovec, MD, MPH

Duke University Medical Center, Durham, NC

Table 1
Summary of Advantages and Disadvantages of Each Neuromonitoring Modality, Including Recommendations for Use

Modality	Advantages	Disadvantages	Uses	Recommendations
TCD	• Noninvasive • Inexpensive	• Variable anatomic window • Anterior fontanelle closes by 9-18 mo • Subjective results • User dependent • Does not indicate flow through smaller cerebral vessels • Dependent on adequate blood flow	• Cerebral blood flow measurement during low-flow CPB • CPB pump flow titration and pulsatility index • Cerebral emboli detection	Use of >1 neuromonitoring modality simultaneously
EEG	• Noninvasive	• Cumbersome equipment • Expensive • Time consuming • Need trained technician	• Obtain preoperative neurologic status • Monitoring during DHCA • Prediction of postoperative seizures and monitor for seizures	
NIRS	• Noninvasive • Able to use throughout perioperative period • Real-time monitoring • More effective than TCD in low-flow states and DHCA	• Limited by location on forehead • Need baseline measurement • Interference by other substances (conjugated bilirubin, methylene blue) • Unreliable if hematocrit >60%	• Monitoring of perfusion during low-flow states (eg, innominate artery cannulation, DHCA) • Adjustment of vasoactive medications, ventilator settings, and CPB indices in response to cerebral saturation changes	

Novel cerebral physiologic monitoring to guide low-flow cerebral perfusion during neonatal aortic arch reconstruction

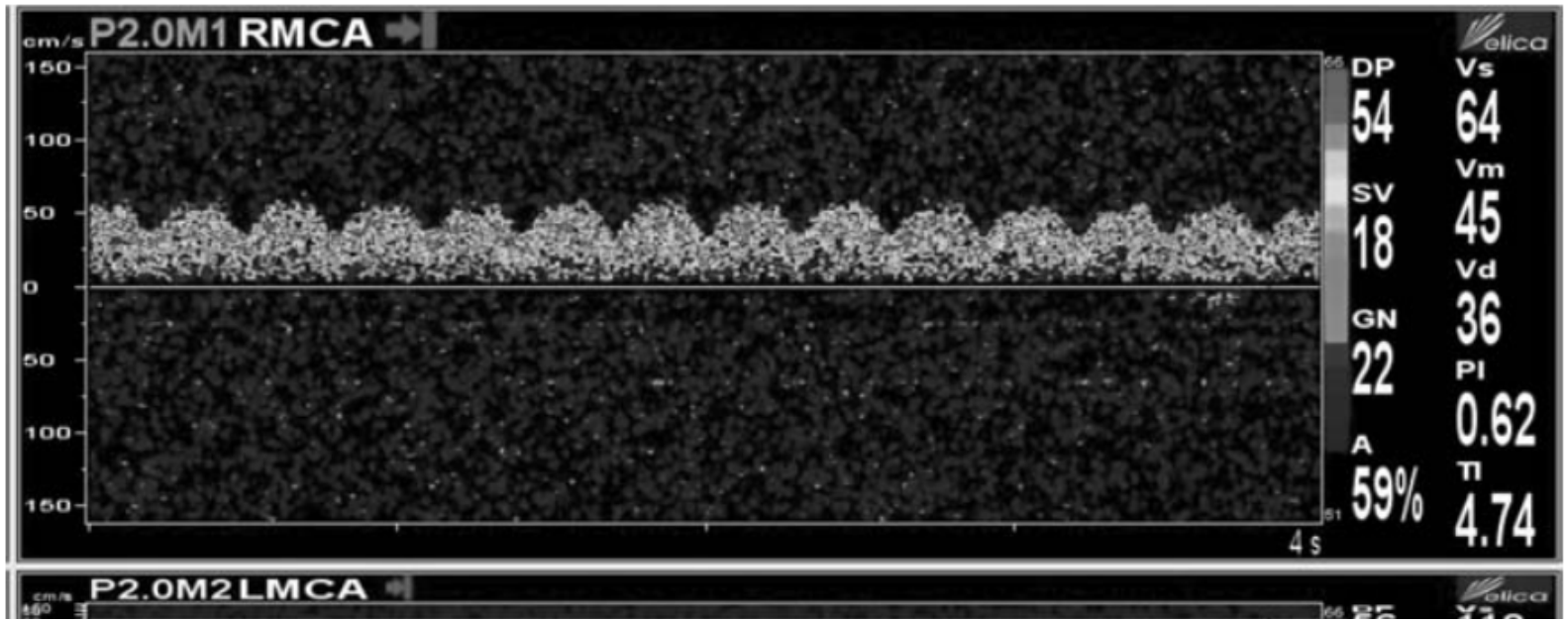
Dean B. Andropoulos, MD[a]
Stephen A. Stayer, MD[a]
E. Dean McKenzie, MD[b]
Charles D. Fraser, Jr, MD, FACS[b]

JCTVS 2003

Real-Time Continuous Neuromonitoring Combines Transcranial Cerebral Doppler with Near-Infrared Spectroscopy Cerebral Oxygen Saturation During Total Aortic Arch Replacement Procedure: A Pilot Study

ASAIO 2012

Xiaohua Wang,* Bingyang Ji,† Baohui Yang,‡ Gang Liu,† Na Miao,§ Jing Yang,§ Jinping Liu,† and Cun Long†



« Bonne » corrélation rSO2 VmMCA (r2= 0.22 Andropoulos et al.)

Table 2. Perioperative Monitoring Parameters

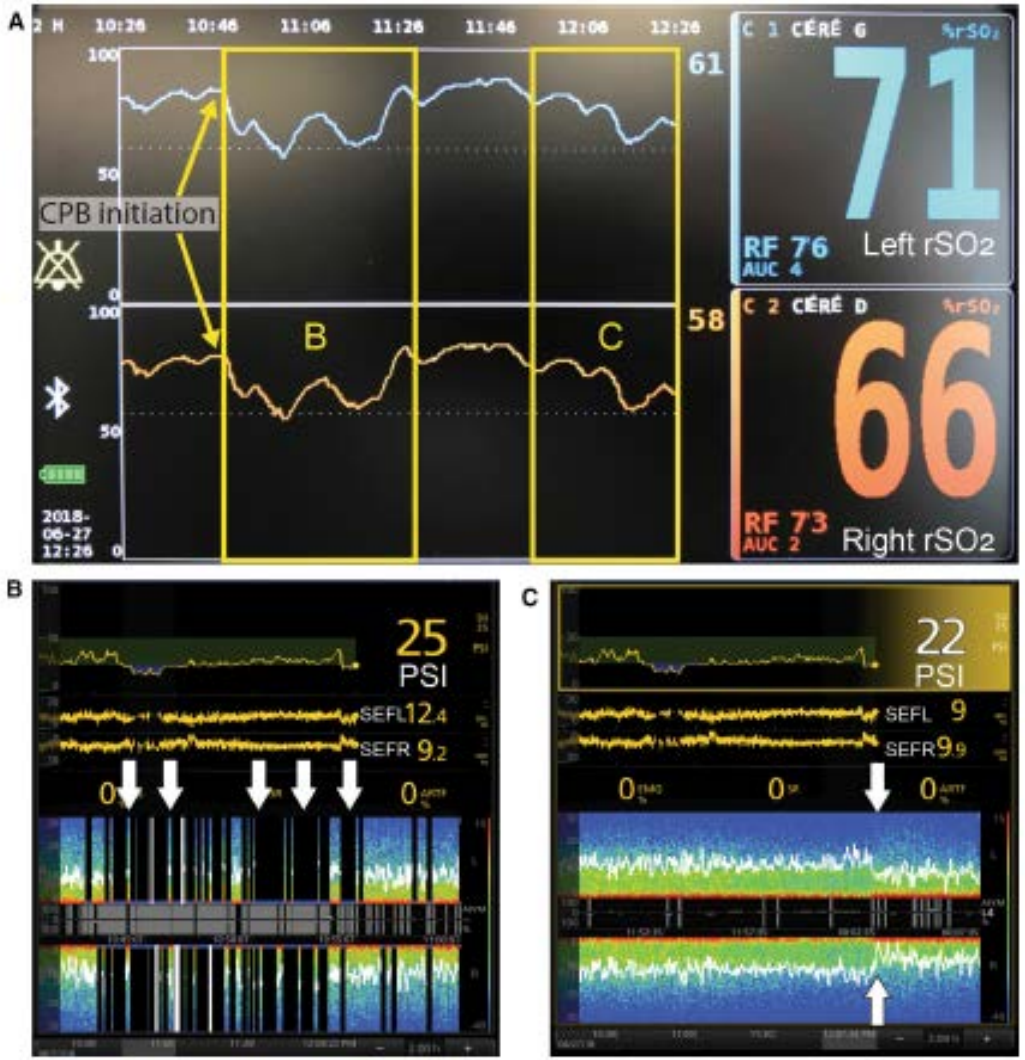
Variable	Pump Flow (ml/min)	Temperature (°C)	MAP (mm Hg)	VmMCA (cm/s)	rSO_2 (%)	SVO_2 (%)
Before incision		36.4 ± 0.7	80 ± 9.2	34.7 ± 14.2	68.8 ± 9.4	
10 min post-CPB	4240 ± 450	30.4 ± 2.4	55.4 ± 9.7	32.7 ± 11.6	63.4 ± 11.6	84.2 ± 5.4
10 min post–cross-clamp	4290 ± 440	26.3 ± 3.6	57.8 ± 11.2	28.9 ± 10.1	57.9 ± 9.8	89.7 ± 6.6
5 min post-ASCP	832 ± 189	21.8 ± 2.8	22 ± 7	15.3 ± 7.2*†	51.4 ± 7.8*	67.4 ± 7.9
10 min post-ASCP	807 ± 214	22.4 ± 2.3	24 ± 6	14.7 ± 6.4*†	52.7 ± 8.9*	61.5 ± 5.8
5 min after full flow	4350 ± 520	21.2 ± 3.1	61.7 ± 13.1	29.4 ± 9.8	55.3 ± 4.5	80.1 ± 9.3
10 min postrewarming	4340 ± 480	28.7 ± 3.9	59.4 ± 9.7	31.3 ± 12.7	54.1 ± 5.8	78.4 ± 7.9
10 min postresuscitation	4370 ± 540	29.7 ± 3.4	58.2 ± 10.2	32.3 ± 12.0	55.4 ± 8.6	77.2 ± 6.5
Postoff pump		36.8 ± 2.4	77.8 ± 14.1	32.7 ± 11.9	53.7 ± 9.1	

*Compared with the induced, $p < 0.05$.
†Compared with post-off pump, $p < 0.05$.
ASCP, antegrade selective cerebral perfusion; CPB, cardiopulmonary bypass; rSO_2, regional cerebral oxygen saturation; VmMCA, middle cerebral artery mean velocity; SVO_2, venous oxygen saturation; MAP, mean arterial pressure.

Patient management algorithm combining processed electroencephalographic monitoring with cerebral and somatic near-infrared spectroscopy: a case series

A Denault CJA 2019

- ✓ Adult patients during CPB
- ✓ PSI: Patient State Index (EMG artifacts)
- ✓ DSA: Density spectral array (=Processed EEG features)
- ✓ Arrows indicate state of suppression EEG



Multimodal Neuromonitoring During Pediatric Cardiac Surgery

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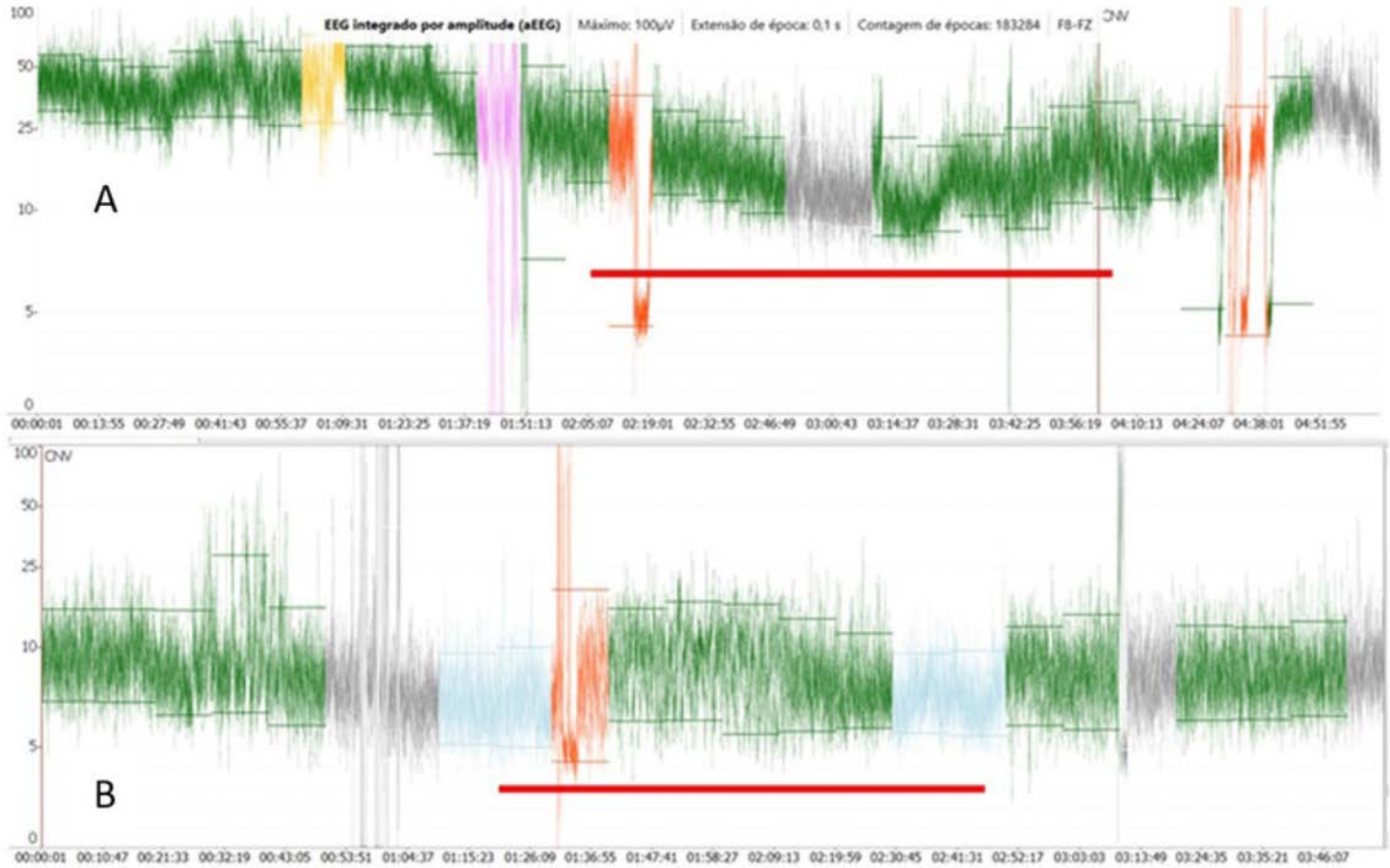
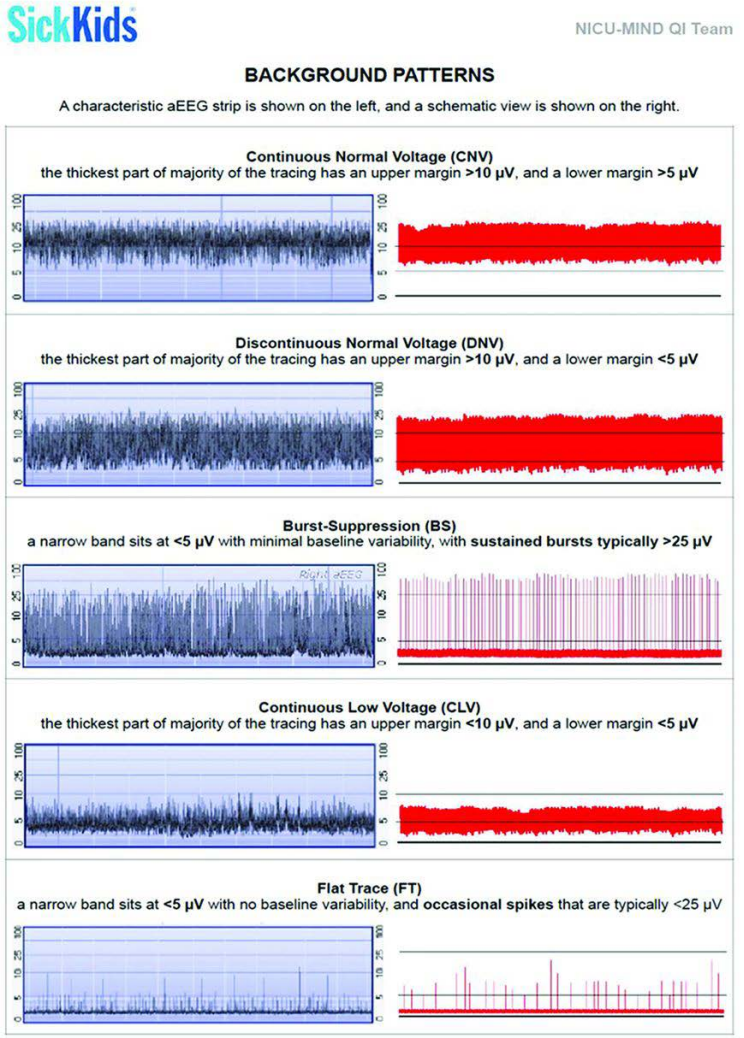
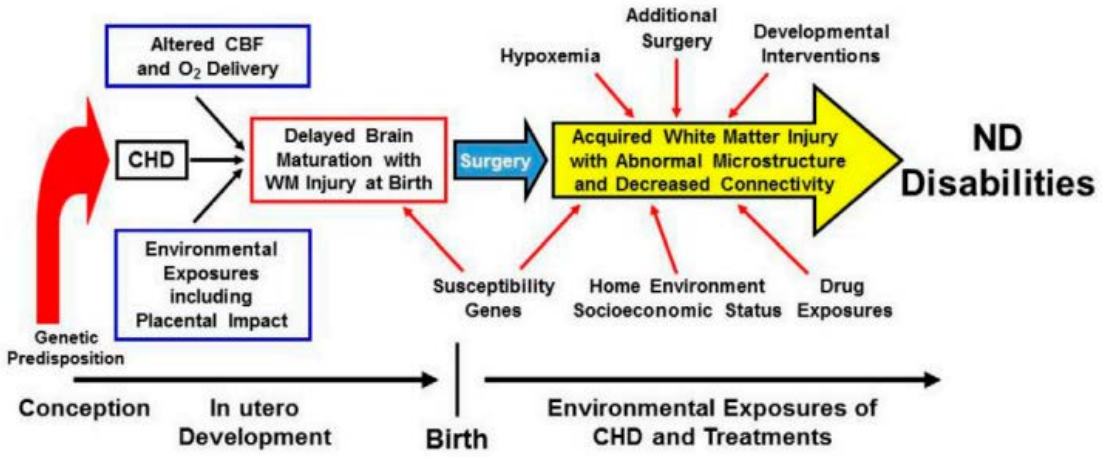


Amplitude Integrated EEG



Conclusion



✓ **NIRS 1ère modalité d'estimation du DSC**

En comprendre les limites:

Association pronostique modeste
Algorithmes non évalués

✓ **DSC optimal = perfusion tissulaire optimale**

✓ Des stratégies de détermination de MAP opt sont à l'étude

✓ TCD: difficile, à associer au NIRS (cf présentation suivante)

✓ EEG: plutôt en post opératoire

PH-STAT

vs

α-STAT

PCO2 corrigée à la température

Principe: ↓du Débit Gaz Frais pendant l'hyporthermie: PaCO2 corrigée stable, PaCO2 non corrigée↑

CBF stable, Améliore DO2 (shift de la courbe de dissociation de l'Hb vers la droite)

Améliore le cooling

« Perte d'autorégulation »

PCO2 NON corrigée à la température

Principe: PaCO2 non corrigée stable (PaCO2 corrigée baisse)

CBF abaissé

« Autorégulation maintenue » (pas d'ajout de CO2)

Fonctions cellulaires préservées à pH alcalin.