Transcranial doppler, EEG and SEP monitoring

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Abstract

The role of neuromonitoring in the prevention of cerebral damage associated with cardiosurgical interventions has not yet been clearly elucidated. Reliable randomised studies from evidence-based medicine showing a clear reduction of risk do not exist. Numerous studies and reviews however, have confirmed that non-invasive procedures for monitoring neuronal or neurophysiological changes before, during and after interventions within the heart or the major thoracic vessels are available and provide early indications of damage.
Technological modalities and clinical indications for non invasive cerebral monitoring were evaluated:
– Electroencephalography (EEG) with processed EEG, bispectral index (BIS) and the evoked potential for use with spinal cord function
– Near infrared spectroscopy (NIRS) for assessment of cerebral perfusion and oxygenation
– Transcranial Doppler sonography (TCDS) for assessment of cerebral circulation and perfusion
– Multimodality monitoring as a combination of EEG, NIRS and TCDS.

Background

The role of neuromonitoring in the prevention of cerebral damage associated with cardiosurgical interventions has not yet been clearly elucidated. Reliable randomised studies from evidence-based medicine showing a clear reduction of risk do not exist. Numerous studies and reviews however, have confirmed that non-invasive procedures for monitoring neuronal or neurophysiological changes before, during and after interventions within the heart or the major thoracic vessels are available and provide early indications of damage [1 – 10].

The incidence of cerebral damage with cardiac or major thoracic vessel operations in adults and children has not improved despite technological developments in monitoring, surgery and perfusion (tab. 1 - 3). It should also be stressed that up until now it has not been possible to create a uniform nomenclature for damage to or functional loss of neuronal structures, so that a reliable form of ensuring comparability still remains an enigma (tab. 4). As regards pathogenesis, numerous covariables exist that may concern the condition of the patient, the surgical procedure, the perfusion technique being used or indeed the mode of anesthesiological management (tab. 5).

Major problems that can lead to reversible, time/intensity-dependent and even irreversible damage to neural structures include:
– Ischaemia (embolisation, perfusion, hypoxia, haemoglobin, oxygen saturation)
– Metabolism (hypoglycaemia, acidosis)
– Electrolyte displacement (hyponatremia)

Here, inadequate perfusion or defective oxygenation can be detected, differentiated and treated early on as potential factors leading to ischemia (tab. 6).

Table 1: Cognitive decline after surgery with cardiopulmonary bypass in percent.

		Observation period				Reference
		1 week	1 - 6 months	5 years		
Newman	1995	73	37			[11]
Newman	2001	53	36/24	42		[12]
Van Dijk	2007			50.4	on-pump	[13]
Van Dijk	2007			50.4	off-pump	[13]

Table 2: Incidence of stroke in a 5-year postoperative period.

				Reference
Van Dijk	2007	1.4	off-pump	[13]
Van Dijk	2007	3.6	on-pump	[13]

Table 3: Differentiated retrospective analysis of the incidence of stroke and delirium with respect to interventions [14].

2003	Σ	2 or 3 fold	mitral	aortic	CABG	CABG	CABG	
n = 16184		valves	valve	valve	+ valve	on pump	off-pump	
%	4.6	9.7	8.8	4.8	7.4	3.8	1.9	stroke
%	8.4				11.2	7.9	2.3	delirium

Table 4: Current nomenclature for damage (left) or functional loss (middle) of neuronal structures with the main resulting residuals (right column).

Neurological injury	Neurocognitive decline	Delirium
Encephalopathy	Neurocognitive dysfunction	Seizures
	Deterioration	Stroke
	Intellectual function	Stupor
	Memory deficite	Coma

Table 5: Covariables with effects on neurophysiological deficiencies

Interventions	Co-Morbidity	Surgical procedures
Coronary artery bypass graft surgery	Extra-, intracranial stenosis	Hypothermia
Open chamber surgery	Arrhythmia	Normothermia
1, 2 or 3 valves	Thrombogenic aortic arch	Management arterial blood pressure
Congenital defects	Age	Off- vs on-pump
Aortic surgery at different levels	Unstable angina	Circulatory arrest
Endovascular procedures (stents, valves)	Diabetes	Separate perfusion

Table 6: The virtuous circle of neurological damage.

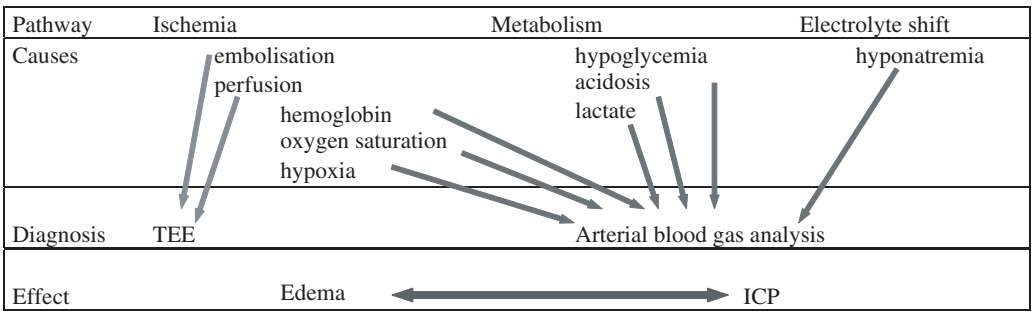

Table 7: Characteristics of non invasive monitoring procedures

Ideal monitor	**Characters**	**TCDS**	**EEG**	**pEEG**	**BIS**	**SSEP**	**tcMEN**	**NIRS**
+++	noninvasive	+++	++	++	+++	++	(+)	+++
+++	continuous	++	++	+++	++	+	+	+++
+++	objective	++	(-)	(+)	-	-	-	+
+++	rapid	+	+	+	+	(+)	+	+
+++	both hemispheres	++	+	++	-			+++
+++	sensor handling	-	-	(+)	+	(+)	(+)	++

From ideal to difficult: +++; ++; +; (+); (-); -; = not intended
TCDS – Transcranial Doppler Sonography; EEG – Electroencephalography; pEEG – Processed Electroencephalography; BIS – Bispectral Index Monitor; SSEP – Somatosensoric Evoked Potentials; tcMEN – Transcranial Motor Evoked Potentials; NIRS – Near Infrared Spectroscopy

Table 8: Synergistic effects of multimodality monitoring.

Ischemia		TCDS	EEG	NIRS
Perfusion	Blood flow	+++	(+)	+
	Embolisation	+++	-	-
Oxygenation	Hemoglobin	-	+	++
	Oxygen saturation			+++
Neuronal function				
Reversibility vs. irreversibility		-	+++	-
Bihemispherial		+	++	+++
Multimodality Monitoring				
Interpretation and decision		++	+	+++
Diagnosis and therapeutic intervention		+++	+++	+++

A range of monitoring procedures (tab. 7 and 8) now allows the detection and assessment of this potential damage early on. Individual procedures have their strengths and weaknesses; so that the effectiveness of a therapeutic measure (and also the detection of a reversible course of damage) can only be described in full if the procedures are combined with one another (multimodality monitoring).

Transcranial Doppler Sonography (TCDS)

Using a 2 MHz pulsed-wave transducer, TCDS [3, 4 - 8, 16 - 23] can be performed through the temporal window for insonation of selected sections of intracranial arterial vessels (tab. 9). The method measures direction and the velocity profile of erythrocytes (fig. 1). The absolute values depend on the insonation angle. The signal provides information about blood when the

Table 9: Characteristics of the Transcranial Doppler sonography (TCDS)

Transcranial doppler sonography (TCDS)					
Measure	cerebral	blood flow velocity relative blood flow changes closing pressure vascular resistance	Limitations	failure - user dependent sensor fixation technical equipment sample volume	10 - 21 % vessel regions
Detect	emboli	gaseous/solid	Advantages	perfusion emboli detection	
Assess	autoregulation			control arterial canula pediatric patients	
Needs	windows	left and right temporal 2 sensors			
	constant insonation				

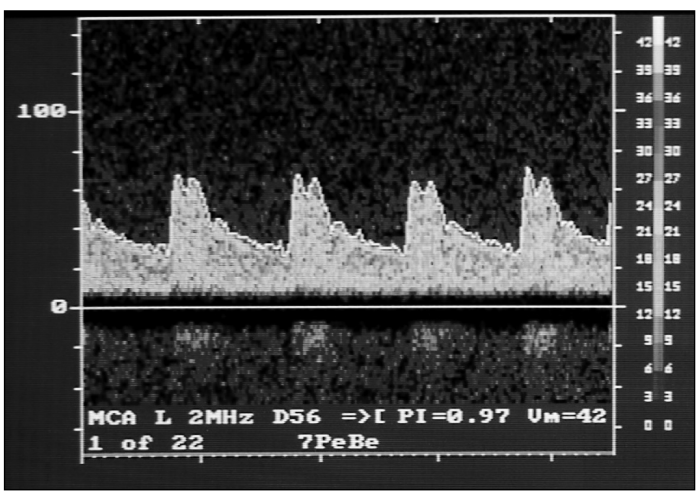

Fig. 1: TCDS signal of the left mean cerebral artery (MCA L) insonated at a depths of 56 mm (D56) with a perfusion index (PI) of 0.97 and a mean velocity (Vm) of 42 cm/sec.

insonation angle is held constant. With holding systems, one sensor each for the right and the left hemispheres can be used continuously during an intervention [21]. Systems are also available that are designed for use during anaesthetic management (mask ventilation, endotracheal intubation, and central venous access) that provide comfort for the conscious patient (fig. 2 and 3) [21]. The system failure rate lies between 3 [22] and 21 % [17], and primarily depends on the investigator. The signals provide clear data on vascular resistance and the preservation of cerebral autoregulation. The critical closing pressure (CCP), which is not a constant value, can be assessed when reducing perfusion during a cardiopulmonary bypass. CCP is the most relevant parameter when assessing regional cerebral perfusion.

Continuously bilateral TCDS recording detects solid and gaseous emboli, whereby high intensity transient signals (HITS) denote severe events (fig. 4) [16]. If severe emboli events are detected, neuroprotective management should be initiated [20]. An erroneous aortal cannulation with a side-differential perfusion or inadequate venous drainage can also be detected immediately so that immediate corrective adjustments can be introduced before any irreversible damage due to deficient cerebral blood flow would otherwise set in within minutes.

One limitation of TCDS is that insonation can only be performed on two vessel sections of interest, and not on the complete circulating system. However, the possibility to insonate vascular sections of the Circulus Willis (fig. 5 and 6) does provide a benefit since

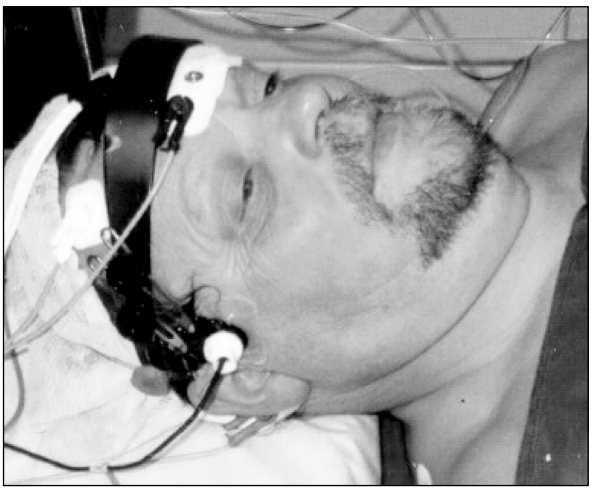

Fig. 2: Multimodal cerebral monitoring with pEEG, NIRS (one sensor) and bilateral TCDS before induction of anesthesia.

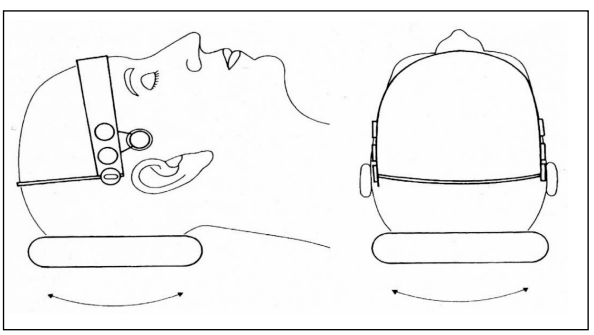

Fig. 3: Degree of handling with the TCDS holding system for use with anesthesia.

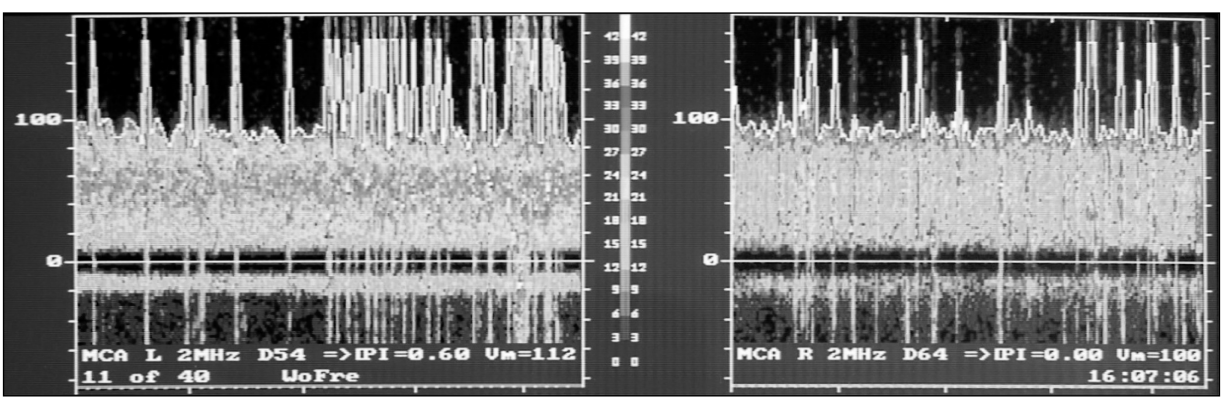

Fig. 4: Embolic signals of air (right) and high intensity transient signals (HITS, left).

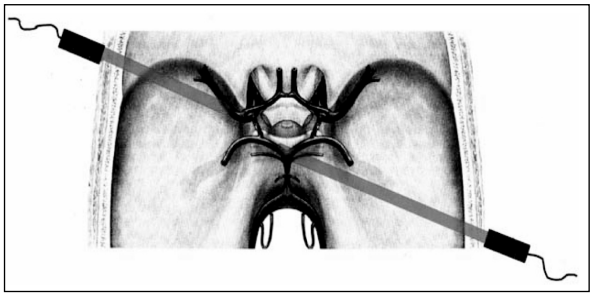

Fig. 5: Use of the left and right temporal window for insonation of two vessel sections (MCA left and PCA with P1 segment on the right).

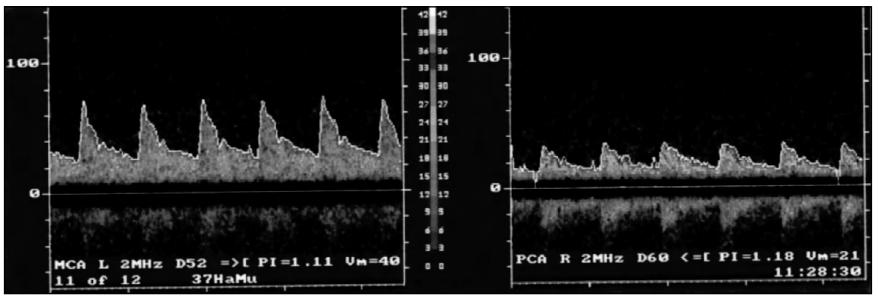

Fig. 6: Corresponding signals revealed from insonation of two vessel sections (MCA left and PCA with P1 segment on the right).

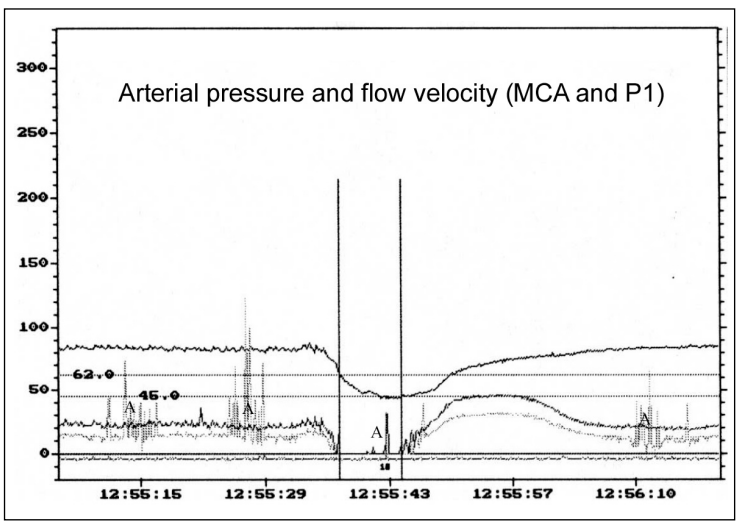

Fig. 7: Continuous recording of the TSDS trends and the corresponding mean arterial pressure for assessment of cerebral autoregulation and cerebral closing pressure. The lines identified the closing pressure when reducing blood flow (left) and with restart (right). The parallel lines to the x axis identified the corresponding pressure.

flow characteristics for central cerebral regions can then be provided.

Cerebral autoregulation and perfusion pressure can be assessed when arterial pressure is continuously recorded in parallel (fig. 7). This allows the measurement of the critical closing pressure in the selected vessel regions (fig. 8).

Electroencephalography (EEG)

EEG reflects the electrical activity of the neuronal structure of the brain [3, 6 - 8, 18 - 20]. Because of physical restrictions on signal recording the method only presents information on the cortex, with subcortical structures largely escaping any assessment (tab. 10). EEG is the most sensitive method for detecting imbalances in cellular function, and can also provide information about the reversibility of injury. It is also the best procedure for detecting seizure activities of a

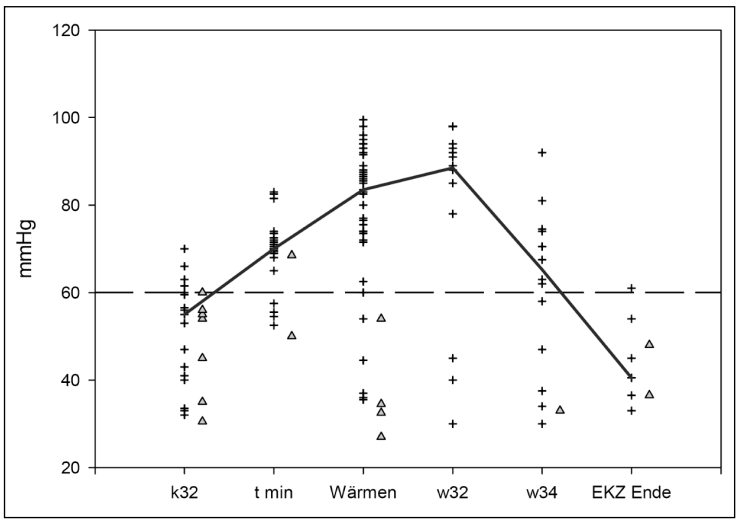

Fig. 8: Corresponding closing pressures of the P1 segment (+) and the MCA (triangle) with respect to cooling and rewarming.

Table 10: Characteristics of the Electroencephalography (EEG)

Electroencephalography (EEG)			
Measure	electrical activity amplitude frequency	Limitations	sensor dependent number location not subcortical structures
Detect	neuronal imbalance cortex		interpretation
		Advantages	neurophysiological imbalance regional discrimination reversibility before damage
Interference	anesthesia pCO2 hypothermia glucose metabolism electrolyte displacement		

(sub)clinical nature during anaesthesia. Depending on the number of sensors fitted according to the standard 10/20 coordinate system (fig. 9), the investigator can acquire either generalised or regionalised information. Cerebral ischaemia induces neuronal dysfunction so that frequencies are slowed or amplitudes are reduced (tab. 11). The latency of return of EEG activity after deep hypothermia cardiac arrest (DHCA) predicts the subsequent neurological outcome [8].

The EEG signal depends substantially on thermomanagement, anaesthetic depth, imbalances in metabolism (hypoglycaemia), and autoregulation combined with the arterial carbon dioxide partial pressure (pCO2 in mmHg). This dependence on anaesthetic depth has led to the introduction of depth-of-anaesthesia monitoring, including the measurement of the bispectral index (BIS). Hypothermia may suppress cerebral activity due to burst suppression and might mask the depth of anaesthesia or any severe cerebral ischaemia. Unexpected consciousness during a cardiopulmonary bypass with hypothermia is a serious anaesthetic complication [24].

EEG is less sensitive for detecting hypoxemia than cerebral near infrared spectroscopy (NIRS), but more sensitive in the detection of recovery. [8].

Electrode handling and signal interpretation are the limitations of EEG. A comparison of baseline data with signals obtained during intervention, and between

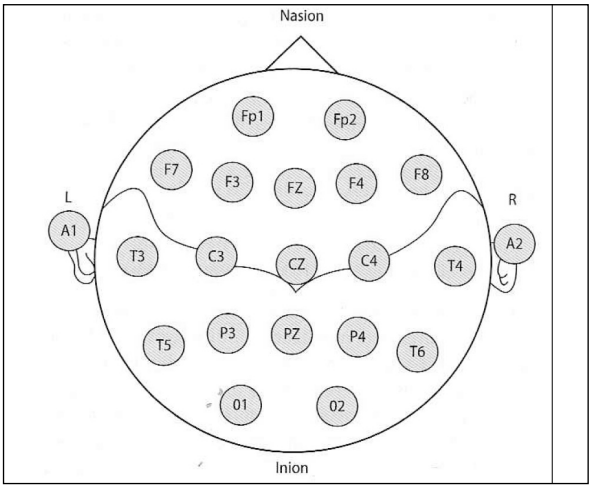

Fig. 9: International 10/20 sensor position system for EEG

Table 11: Characteristic information to EEG bands

Comparison of EEG bands		
Type	Frequency (Hz)	Differential diagnosis
Delta	up to 3	subcortical diffuse lesions metabolic encephalopathy hydrocephalus deep midline lesions.
Theta	4 - 7 Hz	focal subcortical lesions metabolic encephalopathy deep midline disorders
Alpha	8 - 12 Hz	coma
Beta	12 - 30 Hz	benzodiazepines
Gamma	26–100	

those taken from the left and right hemispheres might help to identify an ischaemia.

Processed EEG

Different forms of spectral analysis (processed EEG) from EEG signals allow characterisation of the frequency-power distribution for interpreting whether signals are due to anaesthesia or ischemia, and for facilitating the provision of monitor information and signal display (tab. 12). Quantitative variables can be extracted from the spectra of the frequency and power data. The spectral edge frequency (SEF 95) contains 95 % of the global power, whereas the median describes the 50 % edge. Quantitative power variables are defined as the total power (representing the sum of

Table 12: Characteristics of the processed EEG (pEEG)

Processed EEG (pEEG)	
Measure	frequency-power distribution quantitative variable spectrale edge frequency SEF 95
Assess	both hemispheres frontal - occipital
Advantage	number of electrodes 4 channel
Limitation	objective interpretation

the total power of all frequencies), the relative power for a given frequency band (α-, β-, δ-, and θ-band), and the ratios to the total power.

Bispectral Index™

Unlike classical spectrum analysis, bispectral analysis also quantifies the phase spectrum and reports a dimensionless BIS value of between 100 (awake) and 0 (no EEG-activity) [25, 26]. The BIS value allows an assessment of sedation, sleep and the effects of anaesthesia. Changes can occur due to the influence of opioids or hypothermia. Muscular artefacts disrupt the crude EEG which is also displayed and filtered out (tab. 13). Up until now mainly one sensor is used with 2 measurement electrodes and an indifferent electrode on the forehead according to the equivalent positions of the 10/20 scheme so that no hemisphere differences are recorded. A sensor system assessing both hemispheres is currently launched. Any unnoticed consciousness during interventions with a heart lung machine or during hypothermia represents a clear danger; it emphasises the importance of using the BIS monitor to control the depth of anaesthesia rather than for monitoring neuronal function.

Somatosensorically-evoked potentials (SSEP)

Somatosensorically-evoked potentials [3, 15, 27 – 31] (tab. 14) are cortical and subcortical responses to the stimulation of peripheral nerves (fig. 10). For the purposes of signal production the data from individual stimulations are added or averaged (> 100). Depending on the point of stimulation, early, middle and late latency times are defined which are associated with their corresponding conduction pathways. Positive

Table 13: Characteristics of the Bispectral Index Monitoring (BIS)

Bispectral Index (BIS)		
Measure	classical spectrum analysis with phase spectrum	
Reduce	number of electrodes	1 sensor 2 channel electromyography
	artefacts	
Advantages	1 value between 100 and 0	
	Hypnosis and sedation	(avoid awareness)
	resistent to artefacts	
Limitations	Protection not evidence based	
	1 hemisphere	
	designed to measure anesthetic effect	

Table 14: Characteristics of the Somatosensoric Evoked Potentials (SSEP, SEP)

Somatosensoric Evoked Potentials (SSEP, SEP)	
Measure	cortical and subcortical response to peripheral nerve stimulation 200 averaged data sets assessment of spinal cord injury
Assess	10/50 rule sensoric pathway
Advantage	pre/post changes prognostic value to mortality
Limitations	low sensitivity to delayed neurological deficite

events are labelled with a P, and negative with an N, while the subsequent number usually declares the latency time of the event in msec. For the stimulus position of the median nerve a typical negative wave N20 results, while the characteristic curve for the posterior tibial nerve is labelled as P35. A reduction of amplitude of 50 % and a prolongation of the latency time by 10 % indicates an ischaemia. SSEP-monitoring originates from intact sensory conduction pathways and is compared with the baseline before the intervention (10/50 rule). Wherever damage has occurred a quantitative analysis is insufficient.

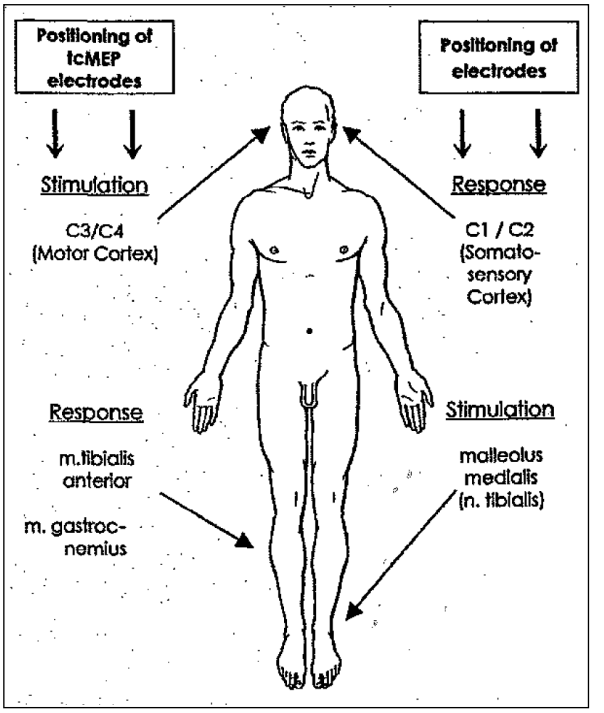

Fig. 10: Principles of Evoked Potentials (EP) for the assessment of spinal cord injuries during aortic aneurysm repair. TcMEP on the left side and SSEP on the right side.

Transcranial motor evoked potentials (tcMEP)

In order to test the motor conduction pathways as well, the stimulus responses can be derived as electrical potentials from their corresponding muscles through transcranial electrical or magnetic stimulation of the cortex [27 – 30](tab. 15). While the extremely painful electric stimulation can only be applied during deep anaesthesia, transcranial magnetic stimulation can also be applied during a postoperative follow-up. Stimulus application and responses can be safely reached using percutaneous needles under anaesthesia. Anaesthesia procedures and neuromuscular blockade can significantly alter the outcome and must be considered during interpretation. Here as well the comparison with baseline before the intervention is the key aspect of the analysis.

Near-Infrared Spectroscopy (NIRS)

The procedure [5, 6, 8, 18, 19, 23, 33 - 35] (tab. 16) is based on the subtraction of signals from 2 to 4 wavelengths in the range from 700 and 1000 nm and on the

Table 15: Characteristics of the Transcranial Motor Evoked Potentials (tcMEP)

Transcranial motor evoked potentials (tcMEP)	
Measure	response of M. tibialis anterior/gastrocnemicus to central motor cortex stimulation transcutaneuos magnetic stimulation percutaneous stimulation with needles painful
Assess	10/50 rule descendence motoric pathway
Advantage	postoperative magnetic stimulation
Limitations	percutaneous needles painful

Table 16: Characteristics of the Near-infrared Spectroscopy (NIRS)

Near-infrared Spectroscopy (NIRS)	
Measure	tissue absorption 2 to 4 wavelength (LED or laser) 700 to 1000 nm sensitive to oxygen saturation hemoglobin cytochrome a/a3
Assess	mixed venous/arterial saturation
Advantages	both hemispheres continuous signal handling
Limitations	small sample volume cortex calibration procedure relative changes prognostic value

ability to adequately penetrate tissues and skull bone in the area applied. The subtraction is achieved in such a way that in addition to an emitter there are also two detectors lying one centimetre apart that record the signal. Depending on the absorption by the tissue and the path that the photons must cross, the proportion of signal which penetrates the cerebral cortex in the marginal zones can be extracted. The so called „sample volume“ of the sensor can vary very much between individuals. Absolute values can only be given for the regional cerebrovenous oxygen saturation (rCVOS) in percent, since this is a ratio obtained from the signals of 2 wavelengths. The proportion of arterial and venous blood lies between 25/75 and 15/85 %, so that differences from the measured jugular venous bulb oxygen saturation (SjvO2 in %) can materialise if the device is not calibrated to this figure. A clear diagnosis of a hypoxia, i.e. a defective oxygen partial pressure in the tissue < 22 mmHg, can not be reliably made from the oxygen binding curve. In addition the NIRS-signal can also be contaminated by tissues and extracranial vessels.

Due to the easy handling and the ability to fix two sensors on the forehead this non invasive monitoring develops a career like the pulse oximetry: there is no evidence based information about outcome benefit, but it delivers clear physiological information about tissue oxygenation at the sample volume. Effects of perfusion restriction with associated ischemia and the corresponding recovery with respect to differences between hemispheres can be monitored (fig. 11).

Multimodality monitoring

Simultaneous neurological monitoring – TCDS, processed EEG and NIRS – may hold the greatest promise for detecting and correcting neuronal dysfunction and later occurring neurological defects [2, 6, 19] (tab. 17). With combined use of TCDS to measure blood flow in the middle cerebral artery (MCA) and NIRS to measure rSO2 in the frontal lobe, and in both hemispheres as well, it is possible to monitor up to 70 % of the blood flow distribution.

Monitoring perfusion with TCDS, oxygenation with NIRS and the resulting neuronal imbalance with pEEG can clearly identify the cause of injury and may assist in choosing the appropriate corrective measures. The highly sensitive EEG-alterations can help differentiate between the effects of hypothermia and anaesthetic depth.

In patients with congenital heart defects, Austin et al. [19] introduced a treatment algorithm. When the abnormal monitoring values were treated, the incidence of adverse outcome decreased to 7 %, similar to the 6 % value obtained from patients without abnormal values.

Multimodality neuromonitoring is also supported by the fact that injury to the brain is a multifactorial process.

Documentation

There is currently no standardized documentation chart available for neurophysiologic monitoring and

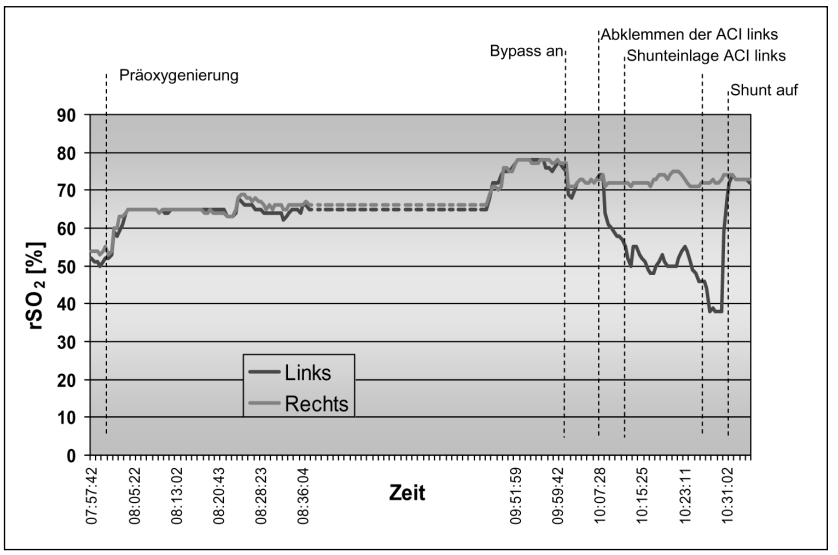

Fig. 11: NIRS forehead sensors during clamp of the left internal carotic artery (ACI left). Graph from M. Heringlake with permission).

Table 17: Characteristics of the Multimodality Monitoring

Mulimodality Monitoring		
Measure	perfusion	TCDS
	oxygenation	NIRS
	neuronal imbalance	EEG
Assess	up to 70 % blood flow	
	side-different effects to perfusion	
	incidence of embolic events	
	highly sensitive to	oxygen saturation
		hemoglobin
Advantages	differential diagnosis	
	target treatment	
	reversibility	
Limitations	sensor group	
	skin space	
	additional monitors	
	experience with interpretation	

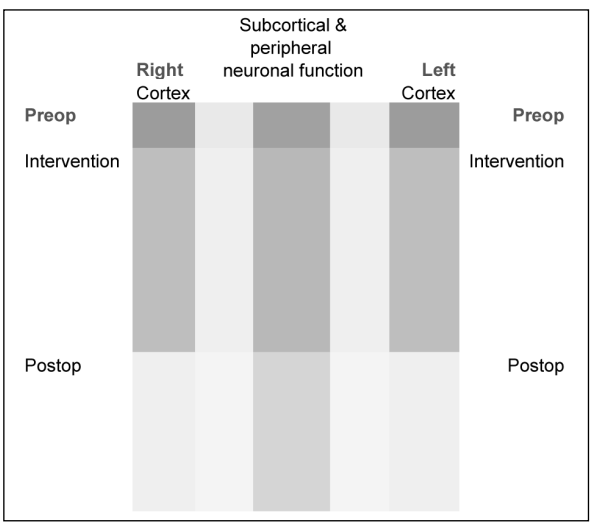

Fig. 13: Chart for perioperative documentation of neurological monitoring and damages.

changes. With respect to the pre- and post interventional periods and with the left and right central nervous structures we propose a brain chart (fig. 12).

Outlook

TCDS

TCDS is restricted by the necessary handling of the probes – the use of a continuously applied sensor holding device or adding ultrasound gel. The application can only be indicated with detection from emboli where arterial cannulation of a thrombogenic aortal arch has been carried out, or in patients with vascular disease who require a higher cerebral perfusion pressure or for whom the leading vessels are stenosed. Amongst young patients with inborn cardiac defects there is a much wider range of application due to the reliable accessibility of the intracerebral vessels through the temporal window, the information regarding cerebral bloodflow and vascular resistance, as well as the autoregulation. However, health insurances do not cover its widespread usage in heart surgery in the USA [lit].

EEG

Global EEG-analysis is not routinely applied during cardiosurgical interventions. Because of the very simple application of pEEG and BIS, these procedures can certainly be used for neuromonitoring, since it is also possible to assess the depth of anaesthesia. Here as well risk patients should receive special attention, since information provided by the BIS procedure does not currently allow any clear decisions to be made about treatment. Despite all attempts to introduce and establish dimensionless scales as single parameters, use of the monitor depends largely on the anaesthetist's personal experience.

NIRS

The simple handling, inexpensive electrodes and the clear information provided about cerebral oxygenation and perfusion (also where the two hemispheres are compared) all go hand-in-hand to recommend this procedure as a standard for cardiosurgical intervention.

Adverse effects of neuromonitoring

The area on the forehead, the positioning and the space required for the fitted sensors often present limitations for the procedure, especially where congenital heart surgery is being conducted in children.

Preparation of the skin and sensor pressure can lead to irritation, although more often than not this is self-restricted. Commercial holding devices are available for continuous bilateral TCDS recording. Potential effects on eyes and ears should be considered; the patient should best be awake and able to seek help. All sensors should be visible and checked periodically by the anaesthesiologists.

Signal loss might be caused by perfusion or by a displacement of the sensor on the skin. It therefore requires some experience in TCDS to allow a fixed position of the sensors to be maintained.

Conclusion

Impairment of cerebral function is a multifactorial process. The most important parameters for continuous monitoring procedures are the comparisons:
1. to the baseline before intervention, and
2. between the two hemispheres.

The sensitivities of NIRS for ischemia, TCDS for perfusion, EEG for neuronal function and EP for sensory and motor neuronal function have all been adequately proven, whereby multimodal application of the procedures optimises the informative value regarding cause, therapy and effect. The failure of TCDS and EP alone stresses the importance of the simple and standardised application of NIRS. The use of bilateral and unilateral TCDS or SSEP/tcMEP is indicated for special areas of application.

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