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Correlation between Cerebral Oxygen Saturation Measured by Near-infrared Spectroscopy and Jugular Oxygen Saturation in Patients with Severe Closed Head Injury

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Background: Near-infrared spectroscopy has been used to monitor cerebral oxygen saturation during cerebral circulatory arrest and carotid clamping. However, its utility has not been demonstrated in more complex situations, such as in patients with head injuries. The authors tested this method during conditions that may alter the arteriovenous partition of cerebral blood in different ways.

Methods: The authors compared changes in measured cerebral oxygen saturation and other hemodynamic parameters, including jugular venous oxygen saturation, in nine patients with severe closed head injury during manipulation of arterial carbon dioxide partial pressure and after mean arterial pressure was altered by vasopressors.

Results: The Bland and Altman representation of cerebral oxygen saturation versus jugular oxygen saturation showed a uniform scatter. Values for changing arterial carbon dioxide partial pressure were: bias = 1.1%, 2 SD = ±21%, absolute value; and those for alterations in mean arterial pressure: bias = 3.7%, 2 SD = ±24%, absolute value. However, a Bland and Altman plot of changes in cerebral oxygen saturation versus changes in jugular oxygen saturation had a negative slope (alteration in arterial carbon dioxide partial pressure: bias = 2.4%, 2 SD = ±17%, absolute value; alteration in mean arterial pressure: bias = -4.9%, 2 SD = ±31%, absolute value). Regression analysis showed that changes in cerebral oxygen saturation were positively correlated with changes in jugular venous oxygen saturation during the carbon dioxide challenge, whereas correlation was negative during the arterial pressure challenge.

Conclusions: Cerebral oxygen saturation assessed by near-infrared spectroscopy does not adequately reflect changes in jugular venous oxygen saturation in patients with severe head injury. Changes in arteriovenous partitioning, infrared-spectroscopy contamination by extracerebral signal, algorithm errors, and dissimilar tissue sampling may explain these findings. (Key words: Brain; hemodynamics; spectroscopy; transcranial Doppler.)

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NEAR-INFRARED spectroscopy (NIRS) is a method for continuous, noninvasive monitoring of cerebral oxygen saturation (Sc_{O_2}). Its accuracy depends on distinguishing the signal reflected by the brain from that reflected by other tissues (skin, muscle, bone).^{1,2} Several studies have shown that when used in normal human subjects, NIRS responds rapidly to cerebral oxygen desaturation during marked cerebral hypoperfusion or systemic hypoxia.³⁻⁵ However, because severe hypotension (e.g., circulatory arrest) influences both cerebral and extracerebral compartments, such studies do not validate the technique or at least do not prove its value in more complex situations. For example, NIRS detects only a fraction of the pathologic events identified by parallel multimodal monitoring in human head injury.⁶ Moreover, when NIRS is used in an intensive care setting, changes in cerebral blood flow (CBF) or vascular

tone may modify the arteriovenous (AV) distribution of blood in the brain differently from the distribution in scalp and in other extracerebral tissues. All of these phenomena may considerably distort ScO_2 . The present study therefore examines the relations between NIRS ScO_2 and jugular venous oxygen saturation ($SvjO_2$) during changes in arterial carbon dioxide partial pressure (Pa_{CO_2}) and blood pressure in adults with head trauma. Our working hypothesis was that these tests produced different effects on CBF and AV partition, thus identifying some of the limitations of NIRS in clinical use.

Materials and Methods

Materials

This study was approved by the ethics committee of the hôpital H. Mondor, Créteil, France, and informed consent was obtained from patients' next of kin. Nine patients with severe closed head injury (Glasgow Coma Scale < 8) and with multifocal contusions or diffuse brain swelling confirmed by computed tomography scan were studied within the first 10 days after injury. Patients with bilateral frontal contusions were not included. In order to be able to measure all signals on the same side, patients who had focal contusions on the side of the dominant jugular vein were also excluded. All patients were placed in the supine position with the head and thorax tilted upward at 30°. They were sedated with midazolam and fentanyl and were ventilated mechanically to achieve 100% arterial oxygen saturation (Sa_{O_2}) and moderate hypocapnia (Pa_{CO_2} 30–35 mmHg). Patients who had a mean arterial pressure (MAP) < 70 mmHg were given a norepinephrine infusion to maintain arterial pressure above this threshold before the start of the study. All patients had normal core temperature and blood hemoglobin level > 10 g/100 ml.

A retrograde jugular catheter (Opticath 5.5 French; Abbott, Rungis, France) was placed on the side corresponding to the dominant jugular vein, as assessed by intracranial pressure (ICP) increase during a compression test.⁷ The position of the catheter in the jugular bulb was confirmed by radiograph. ScO_2 was recorded by NIRS (Invos 3100; Somanetics, Troy, MI). This system used two wavelengths: 730 and 810 nm. The sensor contained a near-infrared light-emitting diode, and two light detectors located 30 and 40 mm from the light-emitting diode, to distinguish between the cerebral and extracerebral signals and thus monitor the ScO_2 in the underlying area of the brain. The sensor was placed on the upper forehead, on healthy skin, 4–5 cm from the

midline, ipsilateral to the jugular catheter. Background light was excluded by an opaque cap. The blood flow velocity in the middle cerebral artery (MCAv) was recorded unilaterally by pulsed Doppler ultrasound (Angiodyne; DMS, Montpellier, France), which was placed on the same side as the NIRS probe. The jugular catheter was always ipsilateral to both ScO_2 and Doppler probes.

The following parameters were recorded at 200 Hz (Labview 4.0; National Instrument, Austin, TX) and averaged every 4 sec: ICP (ventricular catheter), MAP (radial catheter), end-tidal CO_2 (P_{ETCO_2} ; Merlin, Hewlett Packard, Les Ulis, France), MCAv, and ScO_2 . All signals were stored for off-line analysis. $SvjO_2$ was determined by sampling blood *via* the jugular catheter.

CO_2 Challenges

Jugular blood samples were taken and ScO_2 was simultaneously recorded at three levels of P_{ETCO_2} : (1) during moderate hyperventilation (Pa_{CO_2} : 30–35 mmHg, T_0); (2) during intense hyperventilation (Pa_{CO_2} : 20–25 mmHg, T_1); and (3) during a short period of moderate hypercapnia induced by CO_2 inhalation (T_2). CO_2 inhalation was achieved by connecting the air inlet of the ventilator to a chamber (AGA, Toulouse, France) containing 5% CO_2 in 95% O_2 . The inspiratory CO_2 could thus be changed by altering the setting on the ventilator for fraction of inspired oxygen without altering the rate of ventilation or the tidal volume. $SvjO_2$ was not allowed to decrease to < 50% during hyperventilation, and ICP was not allowed to increase to > 35 mmHg during CO_2 inhalation. To standardize the procedure, the order of changes in Pa_{CO_2} was the same in all patients.

Jugular blood samples were taken in the basal state (T_0), during hypocapnia (T_1), and during hypercapnia (T_2). Steady state was maintained for at least 2 min (range, 2–10 min) at T_0 and T_1 . The rapid increase in ICP at T_2 made it impossible to reach steady state. All patients underwent two or three CO_2 challenges, with an interval of at least 24 h between each.

An equivalent of cerebral vascular resistance (Eq_{CVR}) was estimated from the ratio of cerebral perfusion pressure (CPP) to MCAv as proposed by Aaslid *et al.*⁸ Changes in each variable studied during CO_2 challenge corresponded to the difference between the reading after the test minus that measured before the test.

Changes in Systemic Arterial Pressure

A formal test of the response to change in arterial pressure was performed once in each patient and was started after 20 min of steady state after the end of the

first CO₂ challenge. Therefore, the systemic arterial pressure was pharmacologically modified under the same level of moderate hypocapnia as that achieved at T₀. This was performed once in each patient by starting or increasing the rate of norepinephrine infusion (n = 4) or by discontinuing or reducing in the rate of norepinephrine perfusion (n = 5). Increasing or starting norepinephrine was used in patients whose MAP corresponded to values close to the lower limit of the autoregulatory plateau. Conversely, we stopped or reduced norepinephrine infusion in patients whose MAP was close to the upper limit of the autoregulatory plateau. In all patients, ICP was continuously monitored, and norepinephrine infusion was stopped or restarted (as appropriate) if ICP reached 35 mmHg. We also continuously monitored SvjO₂ via the fiberoptic catheter to ensure that it did not decrease to < 50% during the test. Arterial and jugular blood samples were taken when a stable condition was achieved after a step change in norepinephrine.

Statistical Analysis

Results are expressed as means ± SD. Differences between the means of the parameters determined during the CO₂ challenge, at T₀, T₁, and T₂ were compared by two-way analysis of variance for repeated measurements. The Bland and Altman test⁹ was used to compare the absolute values of ScO₂ and SvjO₂ obtained from jugular blood samples. This test was also applied to changes in ScO₂ (δScO₂) and changes in SvjO₂ (δSvjO₂). The relative δScO₂ for T₀-T₁ and T₀-T₂, were compared with the corresponding δSvjO₂ by linear regression. Data of the pressure test were analyzed in the same way as for the CO₂ challenge.

Results

Carbon Dioxide and Arterial Pressure Challenges

The data (means ± SD) obtained during CO₂ challenge and during changes in MAP are shown in tables 1 and 2. Data of ScO₂ and SvjO₂ were plotted according to Bland and Altman.⁹ We saw a similar scatter of error for both tests (fig. 1): the mean of individual differences (ScO₂ - SvjO₂) for CO₂ and arterial pressure challenges were 1.1 and 3.7. Two SDs of these individual differences amounted to ±21% (absolute value) and ±24% (absolute value) for the CO₂ and arterial pressure challenges, respectively. Individual differences between δScO₂ and δSvjO₂ are shown in figure 2. There was an apparent systematic decrease of individual

Table 1. Values of all Variables during CO₂ Challenge (n = 9)

	T ₀	T ₁	T ₂
Pa _{CO₂} (mmHg)	34 ± 7	26 ± 5†	43 ± 9*
MAP (mmHg)	90 ± 23	88 ± 26	87 ± 19
ICP (mmHg)	15 ± 6	10 ± 5†	29 ± 8*
CPP (mmHg)	74 ± 25	78 ± 28†	58 ± 20*
MCAv (cm/s)	69 ± 25	50 ± 22†	79 ± 27*
ScO ₂ (%)	74 ± 13	69 ± 12†	76 ± 13‡
SvjO ₂ (%)	75 ± 13	61 ± 10†	80 ± 12*
Eq _{CVRI} (mmHg · cm ⁻¹ · s)	1.16 ± 0.44	1.77 ± 0.88†	0.77 ± 0.23*

Values are mean ± SD. Differences between means with *P* < 0.05 are considered to be statistically significant.

MAP = mean arterial pressure; ICP = intracranial pressure; CPP = cerebral perfusion pressure; MCAv = blood flow velocity in the middle cerebral artery; ScO₂ = O₂ saturation in the brain; SvjO₂ = jugular venous saturation; Eq_{CVRI} = equivalent of cerebral vascular resistance.

* Significantly different from T₀ and T₁.

† Significantly different from T₀ and T₂.

‡ Significantly different from SvjO₂ at T₂.

differences between δScO₂ and δSvjO₂ when (δScO₂ + δSvjO₂)/2 increased. This seems to reflect a bias that is not randomly distributed.

To better understand this effect we performed a linear correlation between δScO₂ and δSvjO₂ for both tests (fig. 3). The slopes were both significantly different from unity (*P* < 0.05, with an SE of the slope = 0.033 and 0.11 for the CO₂ and the pressure challenge, respectively). They were positive in the CO₂ challenge but negative in the arterial pressure challenge. Hence, regression shows, in addition to the Bland and Altman analysis, that both tests were not only different in terms of the magnitude of the response but the relationship between δScO₂ and δSvjO₂ during CO₂ and pressure were opposite.

Discussion

The main finding of our study is that ScO₂ assessed by NIRS does not adequately reflect changes in SvjO₂ in patients with severe head injury. Unlike “conventional” hypoxic challenges, we chose to examine effects that could result in changes in the AV partition of cerebral blood volume in a possible contamination by extracerebral signals, and by different tissue fields being monitored. Patients with head injuries were studied rather than normal volunteers. This setting introduced more complexity because any regional difference in cerebral perfusion regimen could increase the discrepancy between SvjO₂ and ScO₂.

Table 2. Variables during Changes in MAP

	Decreasing MAP (n = 5)		Increasing MAP (n = 4)	
	Baseline	Low MAP	Baseline	High MAP
MAP (mmHg)	101 ± 33	65 ± 13*	74 ± 9	121 ± 22*
ICP (mmHg)	15 ± 10	12 ± 7	15 ± 4	13 ± 4
CPP (mmHg)	87 ± 39	53 ± 14*	59 ± 5	108 ± 25*
MCAv (cm/s)	75 ± 28	56 ± 24*	55 ± 9	67 ± 8
Sc _{O₂} (%)	81 ± 14	79 ± 16	69 ± 12	61 ± 8*†
Svj _{O₂} (%)	86 ± 4	77 ± 7*	66 ± 9	78 ± 12*
Pa _{CO₂} (mmHg)	37 ± 3	35 ± 3	35 ± 4	36 ± 4
Eq _{CVRI} (mmHg · cm ⁻¹ · s)	1.24 ± 0.57	1.03 ± 0.38	1.07 ± 0.12	1.61 ± 0.20*

Values are mean ± SD.

MAP = mean arterial pressure; ICP = intracranial pressure; CPP = cerebral perfusion pressure; MCAv = blood flow velocity in the middle cerebral artery; Sc_{O₂} = oxygen saturation in the brain; Svj_{O₂} = jugular venous saturation; Eq_{CVRI} = equivalent of cerebral vascular resistance.

* Significantly different from baseline (P < 0.05).

† Significantly different from Svj_{O₂} at high MAP (P < 0.05).

Arterial Pressure Challenge

An arterial pressure challenge in normal patients should not alter CBF because of autoregulation. Svj_{O₂} should also not vary, as cerebral metabolic rate in oxygen (CMRO₂) was likely to be constant throughout the study. But autoregulatory vasoconstriction^{10,11} could reduce arteriolar blood volume. Venous blood volume should be unaffected if CBF remains constant. Thus, an increase in MAP in a context of effective autoregulation should lead to a decrease in Sc_{O₂} at constant Svj_{O₂}. However, autoregulation is often impaired in patients

with head injuries, as in our patients. Indeed, we observed that Svj_{O₂} and MCAv decreased with decreasing MAP during the hypotensive challenge, despite a 17% reduction in Eq_{CVRI}. Conversely, Svj_{O₂} and MCAv increased during norepinephrine infusion, and Eq_{CVRI} also increased by 50%. Hence, in this condition of partially altered autoregulation, arteriolar vasoconstriction was insufficient to increase cerebral vascular resistance proportionally to cerebral perfusion pressure, and this was accompanied by an increase in CBF. This condition should have led to a decrease in the capillary oxygen gradient, a greater capillary contribution to the arterial

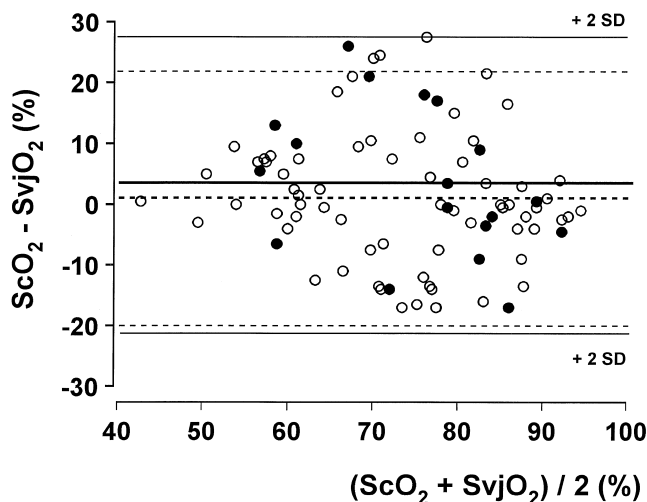


Fig. 1. Bland and Altman test with individual values of cerebral oxygen saturation (Sc_{O₂}) and venous jugular oxygen saturation (Svj_{O₂}). Open symbols: CO₂ test, with upper and lower dotted horizontal line corresponding to ± 2 SD. Middle dotted line represents the bias. Closed symbols: pressure test, with upper and lower solid horizontal line corresponding to ± 2 SD. Middle solid line represents the bias.

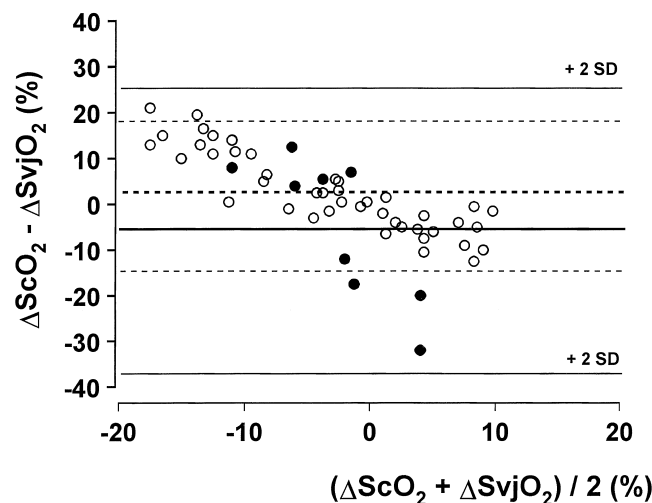


Fig. 2. Bland and Altman test with individual changes in cerebral oxygen saturation (delta Sc_{O₂}) and changes in venous jugular oxygen saturation (delta Svj_{O₂}). Open symbols: CO₂ test, with upper and lower dotted horizontal line corresponding to ± 2 SD. Closed symbols: pressure test, with upper and lower solid horizontal line corresponding to ± 2 SD.

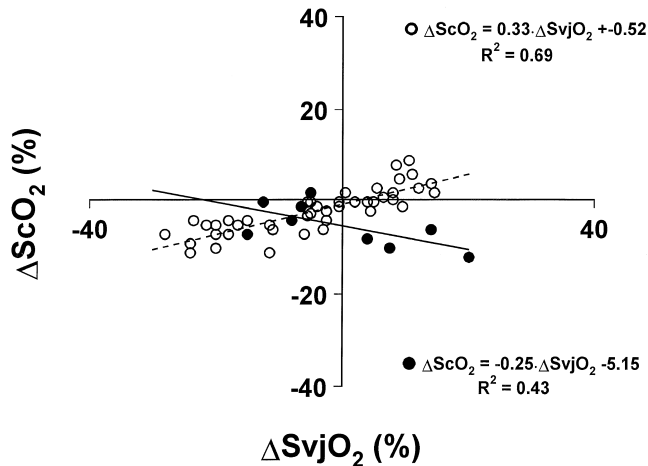


Fig. 3. Correlation between changes in cerebral oxygen saturation (δScO_2) and changes in venous jugular oxygen saturation (δSvjO_2). *Open symbols:* CO_2 test. *Closed symbols:* pressure test. *Dotted and solid lines* represent the regression line of the CO_2 and pressure tests, respectively.

component of the ScO_2 signal, but also to an increase in SvjO_2 and venous blood volume. The opposite phenomena was expected during vasodilation. We observed that δScO_2 and δSvjO_2 correlated negatively when arterial pressure was changed. This tends to support the fact that changes in AV partition should have occurred with a larger increase in the venous compartment than the increase observed in the arteriolar one.

Carbon Dioxide Challenge

The decrease in cerebral vascular resistance in response to vasodilation of the pial arterioles at T_2 was reflected in a 34% decrease in Eq_{CVRI} without change in MAP. Vasodilation should have allowed the volume of the arteriolar compartment to increase. The increase in blood flow at constant cerebral metabolic rate in oxygen should result in an independent increase in the oxygen saturation of the venous compartment and a passive increase in its volume.¹² Hence, hypercapnia, like a change in arterial pressure, may alter the AV partition. However, in contrast to the arterial pressure challenge, we observed a positive correlation between δScO_2 and δSvjO_2 (fig. 3). Thus, the change in AV partition probably occurred during a CO_2 challenge different from that observed during an MAP change. One must also consider possible differential effects on extracerebral tissues. Moreover, ScO_2 , which includes arteriolar blood, would be expected to be higher than SvjO_2 . This was only true at T_2 in our study. All of these issues deserve comment.

First, SvjO_2 could be “artificially high” compared with

ScO_2 because it incorporated deep brain structures that extract less oxygen than the neocortex structures monitored by NIRS. Second, the cerebral signal could be contaminated by a reflected signal from extracerebral structures (e.g., bone, muscle) with unpredictable partition and O_2 saturation characteristics.

This contamination could account for most of the discrepancies observed between tests. The suggestion that the musculocutaneous territory makes a major contribution to NIRS signals is supported by recent experimental data, which indicate that the CBF measured by NIRS is three times greater when the probe is placed on the dura than when it is measured through the scalp.¹³ Similarly, theoretical and experimental investigations of the propagation of light through the skull have shown that light is poorly absorbed by brain grey matter, as it accounts for only 15% of the total light absorbed.¹⁴

The impact of extracerebral tissues on ScO_2 recording is critical. CO_2 dilates cerebral vessels, as well as those in the musculocutaneous territories such as the forehead and scalp.¹⁵ There should therefore be a parallel between the changes in blood flow in both territories when Pa_{CO_2} is altered. The infusion of norepinephrine when autoregulation is disturbed should lead to a decrease in blood flow in the forehead and scalp and an increase in CBF as MAP increases. Although we did not measure velocity at the site of ScO_2 measurement or in extracerebral tissues, we postulate that opposite responses by extracerebral tissues during changes in CO_2 and MAP, combined with changes in AV partition, could account for our findings. Such circumstances would not occur in studies based on hypoxic challenge because oxygen desaturation occurs simultaneously in all territories during such hypoxic experiments, including the musculocutaneous territory.³ The same criticism can be made about measurements conducted after severe hypotension during ventricular fibrillation.⁵ The inability of studies to cope with complex causes of inaccuracy may explain the persisting questions about the use of NIRS in clinical medicine.

Moreover, the physiology of our patients was not simple. Regional vascular variations may occur in patients with head injuries, with hypoperfused ischemic areas and hyperemic areas, leading to nonuniform oxygen extraction and venous saturation.¹⁶ CBF- CO_2 reactivity and autoregulation may also be patchy.^{17,18} Some investigators suggest that that these may account for the discrepancies between changes in ScO_2 and SvjO_2 .^{19,20} Metz *et al.*²¹ showed, by bilateral SvjO_2 measurement in patients with head trauma, that unilateral SvjO_2 measure-

ment did not reliably reflect ischemic events. In contrast, the difference in Sv_{jO_2} between each side did not change with time. Tateishi *et al.*¹⁹ reached the same conclusion after reporting a fair correlation between δSv_{jO_2} and δSc_{O_2} during changes in Pa_{CO_2} in patients with acute brain disease. This suggests that interhemispheric inhomogeneity may not have had much effect in our study, which considered variations in Sv_{jO_2} and in Sc_{O_2} . However, there may have been some intrahemispheric difference, especially between the anterior cerebral artery territory above which the NIRS sensor was placed and the middle cerebral artery territory, which was monitored by Doppler ultrasound. There is no reason to believe that this difference should be larger than the interhemispheric difference.

NIRS Technology

Apart from the problems originating from AV partitioning and the role of extracerebral tissue previously discussed, there may be other errors in the NIRS. The optical path length and light scattering may vary.²² The technology we used includes a continuous wave and, thus, cannot correct for these sources of error. The limits of this method may also have been reached in our study, where different challenges may have induced differing effects on optical path length and light scattering in addition to the possible influences of the AV partition and extracerebral tissues.

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References

- McCormick PW, Stewart M, Lewis G, Dujovny M, Ausman JI: Intracerebral penetration of infrared light: Technical note. *J Neurosurg* 1992; 76:315-8
- Hongo K, Kobayashi S, Okudera H, Hokama M, Nakagawa F: Noninvasive cerebral optical spectroscopy: Depth-resolved measurements of cerebral haemodynamics using indocyanine green. *Neurol Res* 1995; 17:89-93
- Hampson NB, Camporesi EM, Stolp BW, Moon RE, Shook JE, Griebel JA, Piantadosi CA: Cerebral oxygen availability by NIRS spectroscopy during transient hypoxia in humans. *J Appl Physiol* 1990; 69:907-13
- Smith DS, Levy W, Maris M, Chance B: Reperfusion hyperoxia in brain after circulatory arrest in human. *ANESTHESIOLOGY* 1990; 73:12-9
- Levy WJ, Levin S, Chance B: Near-infrared measurement of cerebral oxygenation: Correlation with electroencephalographic ischemia during ventricular fibrillation. *ANESTHESIOLOGY* 1995; 83:738-46
- Kirkpatrick PJ, Smielewski P, Czosnyka M, Menon DK, Pickard JD: Near-infrared spectroscopy use in patients with head injury. *J Neurosurg* 1995; 83:963-70
- Dearden NM: Jugular bulb venous oxygen saturation in the management of severe head injury. *Curr Opin Anaesthesiol* 1991; 4:279-86
- Aaslid R, Lindgaard KF, Sorteberg W, Nornes H: Cerebral autoregulatory dynamics in humans. *Stroke* 1989; 20:45-52
- Bland JM, Altman DG: Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; 1:307-10
- Kontos HA, Wei EP, Navari R M, Levasseur JE, Rosenblum WI, Patterson JL: Responses of cerebral arteries and arterioles to acute hypotension and hypertension. *Am J Physiol* 1978; 234:H371-83
- MacKenzie ET, Farrar JK, Fitch W, Graham DI, Gegory PC, Harper AM: Effects of hemorrhagic hypotension on the cerebral circulation. 1: Cerebral blood flow and pial arteriolar caliber. *Stroke* 1979; 10:711-8
- Auer LM, MacKenzie ET: Physiology of the cerebral venous system, *The Cerebral Venous System and Its Disorders*. Edited by Kapp JP, Schidek HH. Orlando, Grune and Stratton, 1984, pp 169-227
- Owen-Reece H, Elwell CE, Harkness W, Goldstone J, Delpy DT, Wyatt JS, Smith M: Use of near infrared spectroscopy to estimate cerebral blood flow in conscious and anaesthetized subjects. *Br J Anaesth* 1996; 76:43-8
- Okada E, Firbank M, Schweiger M, Arridge SR, Cope M, Delpy DT: A theoretical and experimental investigation of the effect of sulci on light propagation in brain tissue. *Proc Soc Photo-optical Instrument Engineers* 1995; 2626:2-8
- Davidson D, Stalcup SA, Mellins RB: Systemic hemodynamics affecting cardiac output during hypocapnic and hypercapnic hypoxia. *J Appl Physiol* 1986; 60:1230-6
- Sakas DE, Bullock MR, Patterson J, Hadley D, Wyper DJ, Teasdale GM: Focal cerebral hyperemia after focal head injury in humans: A benign phenomenon? *J Neurosurg* 1995; 83:277-84
- Bouma GJ, Muizelaar JP: Cerebral blood flow, cerebral blood volume and cerebrovascular reactivity after severe head injury. *J Neurotrauma* 1992; 9:S333-48
- Steiger HJ, Ciessinna E, Seiler RW: Identification of posttraumatic ischemia and hyperperfusion by determination of the effect of induced arterial hypertension and carbon dioxide reactivity. *Stroke* 1996; 27:2048-51
- Tateishi A, Maekawa T, Soejima Y, Sadamitsu D, Yamamoto M, Matsushita M, Nakashima K: Qualitative comparison of carbon dioxide-induced change in cerebral near-infrared spectroscopy versus jugular venous oxygen saturation in adults with acute brain disease. *Crit Care Med* 1995; 23:1734-8
- Lewis SB, Myburgh JA, Thornton EL, Reilly PL: Cerebral oxygenation monitoring by near-infrared spectroscopy is not clinically useful in patients with severe closed-head injury: A comparison with jugular bulb oximetry. *Crit Care Med* 1996; 24:1334-8
- Metz C, Holzschuh M, Bein T, Woertgen C, Rothoerl R, Kallenbach B, Taeger K, Brawanski A: Monitoring of cerebral oxygen metabolism in the jugular bulb: Reliability of unilateral measurements in severe head injury. *J Cereb Blood Flow Metab* 1998; 18:332-43
- Kurth CD, Uher B: Cerebral hemoglobin and optical pathlength influence near-infrared spectroscopy measurement of cerebral oxygen saturation. *Anesth Analg* 1997; 84:1297-305