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Cerebral Oxygenation and Hemodynamics During Induction of Extracorporeal Membrane Oxygenation as Investigated by Near Infrared Spectrophotometry

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ABSTRACT. *Objective.* To investigate cerebral oxygenation and hemodynamics in relation to changes in some relevant physiologic variables during induction of extracorporeal membrane oxygenation (ECMO) in newborn infants.

Methods. Twenty-four newborn infants requiring ECMO were studied from cannulation until 60 minutes after starting ECMO. Concentration changes of oxyhemoglobin (cO₂Hb), deoxyhemoglobin (cHHb), total hemoglobin (ctHb), and (oxidized-reduced) cytochrome aa₃ (cCyt.aa₃) in cerebral tissue were measured continuously by near infrared spectrophotometry. Heart rate (HR), transcutaneous partial pressures of oxygen and carbon dioxide (tcPO₂ and tcPCO₂), arterial O₂ saturation (saO₂), and mean arterial blood pressure (MABP) were measured simultaneously. Intravascular hemoglobin concentration (cHb) was measured before and after starting ECMO. In 18 of the 24 infants, mean blood flow velocity (MBFV) and pulsatility index (PI) in the internal carotid and middle cerebral arteries were also measured before and after starting ECMO using pulsed Doppler ultrasound.

Results. After carotid ligation, cO₂Hb decreased whereas cHHb increased. After jugular ligation, no changes in cerebral oxygenation were found. At 60 minutes after starting ECMO, the values of cO₂Hb, saO₂, tcPO₂, and MABP were significantly higher than the precannulation values, whereas the value of cHHb was lower. There were no changes in cCyt.aa₃, tcPCO₂, and HR, whereas cHb decreased. The MBFV was significantly increased in the major cerebral arteries except the right middle cerebral artery, whereas PI was decreased in all measured arteries. Cerebral blood volume, calculated from changes in ctHb and cHb, was increased in 20 of 24 infants after starting ECMO. Using multivariate regression models, a positive correlation of Δ ctHb (representative of changes in cerebral blood volume) with Δ MABP and a negative correlation with Δ tcPO₂ were found.

Conclusions. The alterations in cerebral oxygenation after carotid artery ligation might reflect increased O₂ extraction. Despite increase of the cerebral O₂ supply after starting ECMO, no changes in intracellular O₂ availability were found, probably because of sufficient preservation of intracellular cerebral oxygenation in the pre-ECMO period despite prolonged hypoxemia. The increase in cerebral blood volume and cerebral MBFV may result from the following: (1) reactive hyperperfusion, (2) loss of autoregulation because of prolonged

hypoxemia before ECMO and/or decreased arterial pulsatility, or (3) compensation for hemodilution related to the ECMO procedure. *Pediatrics* 1995;95:555-561; *extracorporeal membrane oxygenation, near infrared spectrophotometry, cerebral oxygenation, cerebral hemodynamics, autoregulation.*

ABBREVIATIONS. ECMO, extracorporeal membrane oxygenation; PaO₂, arterial partial pressure of oxygen; PaCO₂, arterial partial pressure of carbon dioxide; NIRS, near infrared spectrophotometry; saO₂, arterial oxygen saturation; cO₂Hb, oxyhemoglobin concentration; cHHb, deoxyhemoglobin concentration; ctHb, total hemoglobin concentration; cCyt.aa₃, (oxidized - reduced) cytochrome aa₃ concentration; cHb, intravascular hemoglobin concentration; CBV, cerebral blood volume; MBFV, mean blood flow velocity; PI, pulsatility index; HR, heart rate; MABP, mean arterial blood pressure; tcPO₂, transcutaneous partial pressure of oxygen; tcPCO₂, transcutaneous partial pressure of carbon dioxide; CBF, cerebral blood flow.

Extracorporeal membrane oxygenation (ECMO) is used to treat newborn infants with severe respiratory failure who do not respond adequately to conventional treatment.^{1,2} The principle of ECMO is based on prolonged partial cardiopulmonary bypass. The survival rate is over 80%, but cerebrovascular injury is an important complication.^{2,3} Generally, the ECMO patient is hypoxemic for hours before ECMO is started. Induction of ECMO may result in significant changes in cerebral circulation caused by ligation of the right common carotid artery and internal jugular vein, decreased arterial pulsatility because of cardiopulmonary bypass, and rapid changes in arterial partial pressures of oxygen (PaO₂) and carbon dioxide (PaCO₂). However, in humans the effects of these changes on cerebral oxygenation and hemodynamics and their role in the pathophysiology of cerebrovascular injury have not been investigated extensively.

Near infrared spectrophotometry (NIRS) offers the possibility of noninvasive and continuous bedside investigation of cerebral oxygenation in newborn infants.^{4,5} We reported preliminary observations of marked changes in cerebral oxygenation and hemodynamics during induction of ECMO.^{6,7} In this report, we present further data and describe the relation between changes in cerebral oxygenation and hemodynamics and changes in some physiologic variables during induction of ECMO.

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METHODS

Study Population

After obtaining informed parental consent, we studied 24 ECMO patients (17 male and 7 female, gestational age 35.1 to 40.9 weeks, birth weight 2100 to 4330 g). The study was approved by the University Hospital ethics committee. The indication for ECMO was failure to maintain normoxemia despite adequate conventional treatment using mechanical ventilation, sedation, muscle paralysis, and vasoactive drugs. All infants met the established entry criteria for ECMO¹; infants with cerebral hemorrhage or cerebral malformation were excluded. The underlying diseases were congenital diaphragmatic hernia (n = 9), meconium aspiration syndrome (n = 6), sepsis (n = 5), and persistent pulmonary hypertension from other causes (n = 4). During cannulation, the infants were anesthetized with fentanyl. Standard venoarterial ECMO was performed.¹ After starting ECMO, flow rate of the bypass was increased gradually during several minutes until reaching a level (ranging from 136 to 205 mL/kg/min) needed to maintain arterial O₂ saturation (saO₂) between 90% and 100% as measured by pulse oximetry. This flow rate is considerably higher than recommended,¹ but proved to be necessary and was not limited by egress of blood from the venous cannula. Subsequently, the ventilator was set at a lower level for pressure, rate, and fraction of inspired O₂ concentration to minimize barotrauma and O₂ toxicity. Systemic heparinization was established. Medication administered before ECMO was continued during the measurement period.

Near Infrared Spectrophotometry

This technique is based on the spectrophotometric measurement of changes in the absorption properties of hemoglobin and cytochrome aa₃ in the near infrared region, depending on their oxygenation state.⁸ The NIRS equipment used was developed by the Department of Biomedical Engineering and Medical Physics, University of Keele, and produced by Radiometer (Copenhagen, Denmark).⁵ Details of our NIRS measurement have been described elsewhere.⁹ Briefly, near infrared light at 3 wavelengths (904, 845, and 775 nm) was transmitted through the skull by fiberoptic bundles. Using the described algorithm, concentration changes of oxyhemoglobin (ΔcO_2Hb), deoxyhemoglobin ($\Delta cHHb$), total hemoglobin (ΔcTb), and (oxidized - reduced) cytochrome aa₃ ($\Delta cCyt.aa_3$) were calculated from changes in absorption of near infrared light at the 3 wavelengths mentioned. The transmitting and receiving optodes were fixed to the skull at an angle of approximately 90°, one at the anterior fontanelle and the other at the right parietotemporal region. In all infants, the interoptode spacing was greater than 2.5 cm to ensure a constant pathlength multiplying factor,¹⁰ which has been stated to be 4.39 times the interoptode spacing.¹¹ As the optical pathlength is wavelength dependent, some modification of the algorithm has been made.¹² ΔcO_2Hb and $\Delta cHHb$ reflect changes in cerebral O₂ supply, whereas $\Delta cCyt.aa_3$ reflects changes in cerebral O₂ availability.¹³ When the intravascular hemoglobin concentration (cHb) is unchanged, ΔcTb reflects changes in cerebral blood volume (CBV). Measurements were started just before the cannulation procedure and continued until 60 minutes after starting ECMO.

Doppler Ultrasound

After having observed a possible increase in CBV after starting ECMO,⁶ we decided to add Doppler ultrasound investigation to

the study, starting from infant number 7. Therefore, data for Doppler ultrasound investigations are available in only 18 of the 24 infants. Using a 5-MHz pulsed Doppler ultrasound unit (Ultramark 4, Advanced Technology Laboratories, Bothell, WA), the time-averaged mean blood flow velocity (MBFV) in the major cerebral arteries was measured intermittently. The pulsatility index (PI) [(peak systolic blood flow velocity - end-diastolic blood flow velocity)/mean blood flow velocity] was also calculated. The flow velocities in the supraclinoid internal carotid artery were measured by placing the transducer at the anterior fontanelle. Measurement of the flow velocities in the middle cerebral artery in the Sylvian sulcus was performed by placing the transducer 1 to 2 cm in front of the right ear above the zygomatic process.¹⁴ Using this approach, the insonation angle was assumed to be negligible (less than 10°). Blood flow velocities were calculated using the built-in calipers and calculation program. Measurements were performed just before application of the NIRS optodes at approximately 60 minutes before cannulation, and just after removal of the NIRS optodes at approximately 90 minutes after ECMO was started. The changes in MBFV and PI after induction of ECMO were expressed as percentages of their precannulation levels.

Measurement of Physiologic Variables

Using a neonatal monitor (Sirecust 404N, Siemens, Erlangen, Germany), heart rate (HR) and (umbilical) mean arterial blood pressure (MABP) were recorded continuously. The abdominal transcutaneous partial pressures of oxygen (tcPO₂) and carbon dioxide (tcPCO₂) (Transend, Sensormedics Corp, Anaheim, CA) and saO₂ at the foot by pulse oximetry (N 200, Nellcor Inc, Hayward, CA) were also measured continuously. Data on tcPCO₂ and tcPO₂ in three infants and data on saO₂ in one infant were not available because of technical failure. Blood samples for determination of PaO₂, PaCO₂, and cHb were drawn from the umbilical artery catheter just before cannulation and at 60 minutes after ECMO was started. Blood gas values and cHb were not corrected during this period.

Data Analysis

From each continuously recorded variable (cO₂Hb, cHHb, cCyt.aa₃, saO₂, tcPO₂, tcPCO₂, MABP, and HR), we obtained data on a 30-second period from six episodes: (A) just before the start of the cannulation procedure, (B) just before carotid ligation, (C) post-carotid ligation just before insertion of the arterial cannula, (D) just before jugular ligation, (E) post-jugular ligation just before insertion of the venous cannula, and (F) at 60 minutes after starting ECMO (see Fig 1). The differences in the mean values over the 30-second period between C and B, between E and D, and between F and A were calculated to determine the effects of carotid ligation, jugular ligation, and ECMO induction, respectively. First, the changes of the variables were analyzed with a multivariate version of the signed-rank test¹⁵ to protect the overall confidence level. Thereafter, statistically significant variables were analyzed further with the signed-rank test. The *P* values presented in the results are those from the (univariate) signed-rank test. The changes in MBFV and PI at 90 minutes and in cHb, pH, PaO₂, and PaCO₂ at 60 minutes after starting ECMO, related to their precannulation values, were also calculated. Each difference was statis-

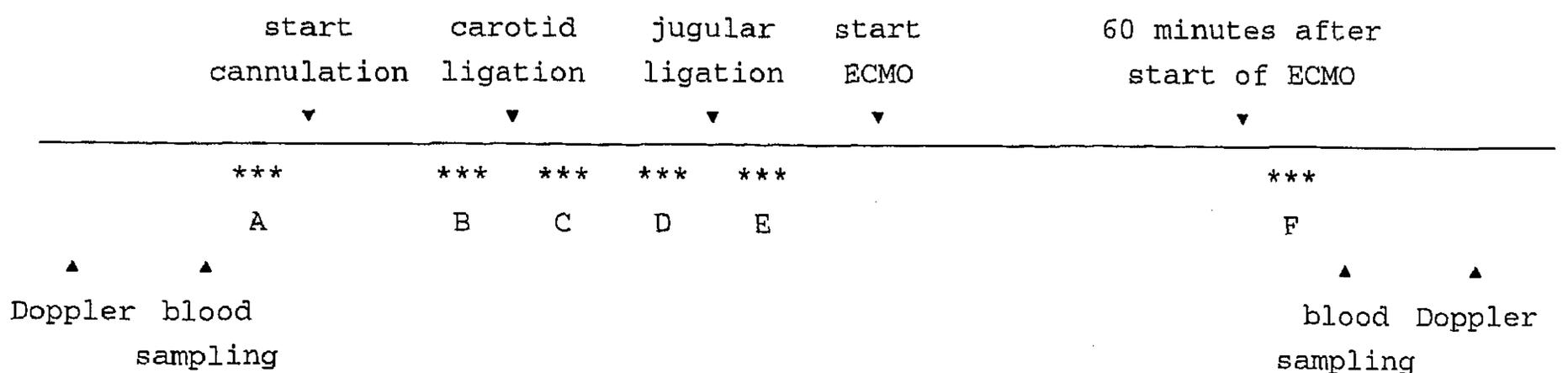


Fig. 1. Schematic representation of data selection from the continuous data registration (see text). ECMO, extracorporeal membrane oxygenation.

tically analyzed by performing the Wilcoxon signed-rank test. For both analyses, the level of significance was .05.

The CBV (expressed in mL/100 g) can be calculated from the following formula:

$$CBV = (4 \cdot ctHb) / (0.69 \cdot cHb),$$

where cHb is expressed in mmol/L and ctHb in $\mu\text{mol}/100\text{ g}$; $0.69 = \text{cerebral-large vessel hematocrit ratio}^{16}$ and $4 = \text{correction factor}$, as ctHb is calculated from changes in light absorption using extinction coefficients based on the tetraheme molecule, whereas cHb determination in blood samples is based on the monoheme molecule.

Because cHb changes after starting ECMO, ΔCBV cannot simply be calculated from ΔctHb . Therefore,

$$CBV + \Delta\text{CBV} = 4 \cdot (ctHb + \Delta\text{ctHb}) / 0.69 \cdot (cHb + \Delta\text{cHb}), \text{ and}$$

$$\Delta\text{CBV} = (\Delta\text{ctHb} - 0.17 \cdot \Delta\text{cHb} \cdot \text{CBV}) / 0.17 \cdot (cHb + \Delta\text{cHb}).$$

However, because the initial CBV in the individual infant is unknown, it is impossible to calculate ΔCBV exactly. Wyatt et al¹⁷ found a CBV value of $2.2 \pm 0.4\text{ mL}/100\text{ g}$ in newborn infants with normal brains. As moderate to severe hypoxemia is the main feature in the pre-ECMO condition, the initial CBV in these infants could be expected to be higher as a result of cerebral vasodilation.^{17,18} Assuming that the pre-cannulation CBV in these hypoxic infants is between 2 and 6 mL/100 g, only the direction of ΔCBV could be estimated:

If ΔcHb is positive: ΔCBV is positive when

$$(\Delta\text{ctHb} / 0.17 \cdot \Delta\text{cHb}) > 6$$

and negative when

$$(\Delta\text{ctHb} / 0.17 \cdot \Delta\text{cHb}) < 2.$$

If ΔcHb is negative: ΔCBV is positive when

$$(\Delta\text{ctHb} / 0.17 \cdot \Delta\text{cHb}) < 2$$

and negative when

$$(\Delta\text{ctHb} / 0.17 \cdot \Delta\text{cHb}) > 6.$$

The distribution of ΔCBV direction among these infants was analyzed by the sign test.

In an attempt to describe the relation between ΔctHb and the changes in selected physiologic variables (ΔcHb , ΔMABP , ΔsaO_2 , ΔtcPO_2 , ΔPaO_2 , ΔtcPCO_2 , ΔPaco_2 , and ΔHR) at 60 minutes after starting ECMO, we assessed possible linear regression models with ΔctHb as a dependent variable and the changes in these selected physiologic indices as independent variables. Because not all physiologic variables were recorded in each infant, regression models could be assessed in only 20 or 21 infants. For the three most suitable models, the regression coefficients (β) and the squared multiple correlation coefficients (R^2) are given. Furthermore, to show the relative contribution to the explanation of the variation in ΔctHb , the partial R^2 (taking into account all other variables in the model) is given.

RESULTS

After carotid ligation, significant decreases in cO_2Hb and MABP were found, whereas cHHb increased. The other variables showed no significant changes. Jugular ligation revealed only an increase in MABP (Table 1; Fig. 2).

Immediately after starting ECMO, increases in saO_2 , tcPO_2 , cO_2Hb , and MABP were observed, whereas cHHb decreased. At 60 minutes after starting ECMO, the variables had stabilized in most infants. By then, values of cO_2Hb , saO_2 , tcPO_2 , MABP, and PaO_2 were significantly higher than the precannulation values. The cHb was significantly decreased because of hemodilution by the ECMO priming solution (Table 2; Fig. 2).

After starting ECMO, MBFV increased significantly in the major cerebral arteries except the right

TABLE 1. Changes in Near Infrared Spectrophotometry and Other Physiologic Variables Related to Carotid and Jugular Ligation (n = 24)*

	Carotid Ligation	Jugular Ligation
$\Delta\text{cO}_2\text{Hb}$, $\mu\text{mol}/100\text{ g}$	-0.36† (-0.76 to -0.18)	0.02 (-0.18 to 0.17)
ΔcHHb , $\mu\text{mol}/100\text{ g}$	0.21† (0.02 to 0.69)	-0.01 (-0.24 to 0.21)
ΔctHb , $\mu\text{mol}/100\text{ g}$	-0.12 (-0.23 to 0.09)	0.06 (-0.11 to 0.21)
$\Delta\text{cCyt.aa}_3$, $\mu\text{mol}/100\text{ g}$	-0.00 (-0.00 to 0.01)	0.00 (-0.00 to 0.01)
ΔsaO_2 , %‡	-0.73 (-3.31 to 0.85)	1.01 (-0.21 to 2.30)
ΔtcPO_2 , mm Hg§	-0.64 (-2.03 to 0.20)	0.03 (-0.46 to 1.95)
ΔtcPCO_2 , mm Hg§	0.22 (-0.38 to 1.03)	0.00 (-0.58 to 1.08)
ΔMABP , mm Hg	-1.90† (-6.41 to 0.32)	1.27† (0.08 to 3.53)
ΔHR , beats/min	-0.16 (-3.56 to 0.85)	-0.55 (-2.15 to 0.82)

* Values are median (interquartile range). Abbreviations: cO_2Hb , oxyhemoglobin concentration; cHHb, deoxyhemoglobin concentration; ctHb, total hemoglobin concentration; cCyt.aa₃, (oxidized - reduced) cytochrome aa₃ concentration; saO₂, arterial oxygen saturation; tcPO₂, transcutaneous partial pressure of oxygen; tcPCO₂, transcutaneous partial pressure of carbon dioxide; MABP, mean arterial blood pressure; HR, heart rate.

† Significant changes ($P \leq .05$).

‡ n = 23.

§ n = 21.

middle cerebral artery (Table 3). However, the direction of the blood flow in the right supraclinoid internal carotid artery was reversed in all infants. The PI values decreased significantly after starting ECMO (Table 3).

The CBV increased in 15 of 24 infants after starting ECMO, which was statistically significant ($P < .01$). In the other nine infants, CBV decreased (n = 2) or did not change (n = 7).

After assessing each possible regression model, we found that a model with five independent variables appeared to be most suitable to describe the relation between ΔctHb and the changes in other variables at 60 minutes after starting ECMO. The best model ($R^2 = .67$) had the independent variables ΔcHb , ΔMABP , ΔtcPO_2 , ΔtcPCO_2 , and ΔPaO_2 . The next two best models ($R^2 = .66$) differed from the best model by substituting ΔPaco_2 for ΔtcPCO_2 and ΔsaO_2 for ΔPaO_2 , respectively. As could be expected, there was a strong correlation between ΔctHb and ΔcHb . In these models, after correction for the influence of the remaining independent variables, there was a positive correlation of ΔctHb with ΔMABP and a negative correlation with ΔtcPO_2 ($P < .05$). There was no statistically significant correlation between ΔctHb and ΔsaO_2 , ΔHR , ΔPaO_2 , or ΔPaco_2 after this correction.

DISCUSSION

Venoarterial ECMO requires ligation of the right common carotid artery. When the collateral circulation through the circle of Willis is completely normal,

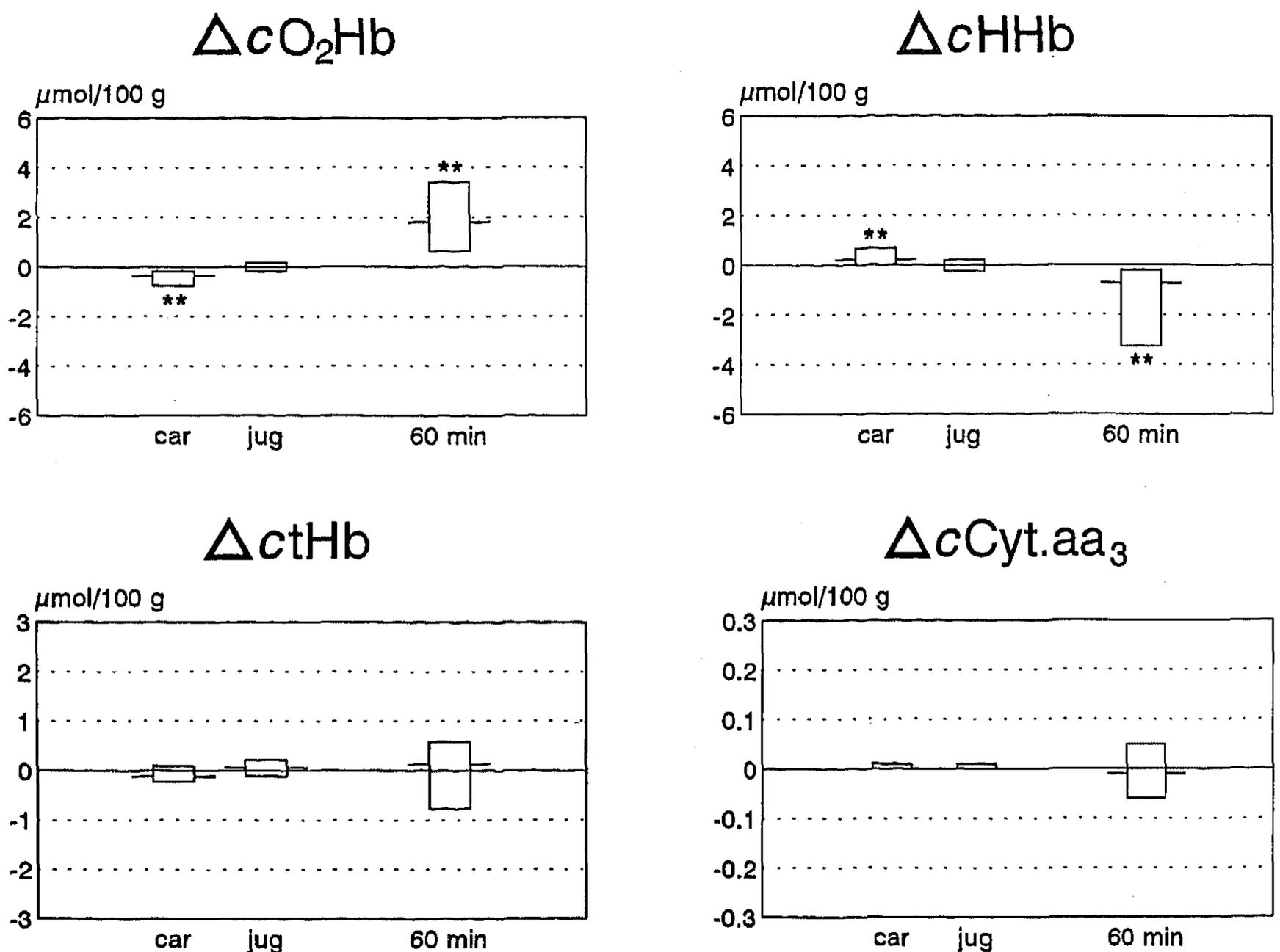


Fig. 2. Changes of NIRS variables during cannulation and after starting ECMO. Car, changes related to carotid ligation; jug, changes related to jugular ligation; 60 min, changes at 60 minutes after starting ECMO as compared with precannulation values. Horizontal line represents the median value; the box covers the interquartile range. cO_2Hb , oxyhemoglobin concentration; $cHHb$, deoxyhemoglobin concentration; $ctHb$, total hemoglobin concentration; $cCyt.aa_3$, (oxidized - reduced) cytochrome aa_3 concentration.

perfusion of the right cerebral hemisphere will be sufficiently preserved. However, because incompleteness of the circle of Willis has been described in 0.6% of normal brains,¹⁹ there is a risk of cerebral infarction in the right hemisphere. Conflicting data on lateralization of cerebral lesions in former ECMO patients have been reported.^{3,20} In our study, $ctHb$ was unchanged after carotid ligation, reflecting unchanged CBV. Assuming unchanged cerebral venous outflow, cerebral arterial inflow must remain unchanged as well. This is demonstrated by our and other Doppler ultrasound studies showing maintained antegrade blood flow in the right middle cerebral artery.^{14,21,22} Reversed blood flow in the right internal carotid artery, as found in our study, is evidence of collateral flow as well. The technique of NIRS may be useful to monitor cerebral hemodynamics during an occlusion test of the right common carotid artery before its definite ligation. When collateral circulation through the circle of Willis reveals inadequacy by showing a fall in CBV, venovenous ECMO should be considered. The advantage of NIRS compared with (color) Doppler ultrasound is the possibility for hands-free continuous monitoring, even during the surgical cannulation procedure.

After carotid ligation, a cO_2Hb reduction with a concomitant $cHHb$ increase was observed. This may reflect increased O_2 extraction in the brain, caused by increased transit time of the blood resulting from

diversion of the arterial blood supply to the right hemisphere. This is supported by the observation that, in contrast to the other major cerebral arteries, the right middle cerebral artery did not show a significant increase in MBFV. This compensatory mechanism is probably sufficient, because there is no significant change in $cCyt.aa_3$, reflecting unchanged cerebral O_2 availability. However, there is doubt about the reliability of the cytochrome aa_3 signal, which will be discussed later.

Ligation of the right internal jugular vein might result in cerebral venous congestion²³ and contribute to the occurrence of cerebral vascular lesions during ECMO.²⁴ However, in our study $ctHb$ and thus CBV did not change after jugular ligation; therefore, it might be concluded that the collateral venous system is sufficient for draining the cerebral venous blood.

The improvement of arterial oxygenation after starting ECMO results in increased cerebral O_2 supply (cO_2Hb). Nevertheless, $cCyt.aa_3$ did not change, reflecting unchanged cerebral O_2 availability, which means sufficient preservation of intracellular oxygenation and energy metabolism in the cerebral tissue in the pre-ECMO period despite prolonged hypoxemia. In newborns, $cCyt.aa_3$ seems to behave more independently from cO_2Hb , as the enzyme remains almost completely oxidized until severe hypoxemia occurs.¹³ However, data on $cCyt.aa_3$ should be interpreted with caution because the algorithm

TABLE 2. Changes of the Measured Variables at 60 Minutes After Starting Extracorporeal Membrane Oxygenation (ECMO) as Compared with Precannulation Values (n = 24)*

	Absolute Precannulation Values	Changes 60 min After Starting ECMO
cO ₂ Hb, μmol/100 g	Not available	1.80† (0.62 to 3.41)
cHHb, μmol/100 g	Not available	-0.72† (-3.27 to -0.20)
ctHb, μmol/100 g	Not available	0.13 (-0.77 to 0.58)
cCyt.aa ₃ , μmol/100 g	Not available	-0.01 (-0.06 to 0.05)
saO ₂ , %‡	76.35 (66.25 to 88.42)	18.60† (4.57 to 30.37)
tcPO ₂ , mm Hg	27.98 (15.83 to 46.35)	47.63† (18.82 to 64.99)
tcPCO ₂ , mm Hg§	41.02 (33.59 to 64.07)	0.15 (-11.71 to 5.43)
MABP, mm Hg	40.56 (34.80 to 50.95)	11.82† (7.01 to 25.32)
HR, beats/min	159.04 (147.34 to 172.80)	-5.16 (-14.31 to 11.66)
PaO ₂ , mm Hg	35.25 (24.37 to 49.87)	59.25† (29.75 to 104.25)
Paco ₂ , mm Hg	38.25 (32.62 to 50.62)	-4.25 (-10.5 to 4.87)
pH	7.34 (7.24 to 7.46)	0.01 (-0.07 - 0.06)
cHb, m Hg	8.75 (7.80 to 9.15)	-1.95† (-2.55 to -0.60)

* Values are median (interquartile range). Abbreviations: PaO₂, arterial partial pressure of oxygen; Paco₂, arterial partial pressure of carbon dioxide; cHb, intravascular hemoglobin concentration; other abbreviations as in Table 1.

† Significant changes ($P \leq .05$).

‡ n = 23.

§ n = 21.

used for calculating Δ cCyt.aa₃ is derived from experiments on rat brains after exchange transfusion with fluorocarbon. Therefore, the data might be affected by noise due to residual hemoglobin after fluorocarbon exchange,²⁵ as well as from scattering by fluorocarbon, which is different from that of erythrocytes.

After induction of ECMO, we observed an increase in CBV, which may result from increased arterial inflow or decreased venous outflow.²⁶ Venous outflow decrease is unlikely to occur because during ECMO, venous blood is drained continuously from the right atrium. Increased arterial inflow is more likely the cause of increased CBV, as MBFV in the major cerebral arteries increases significantly, reflecting increased cerebral blood flow (CBF).²⁷ A high correlation between CBF and CBV changes has been shown in animals.²⁸ There is no clear-cut explanation for the increases of CBF and CBV after induction of ECMO. Data from the literature are contradictory. Induction of ECMO in normoxemic animals has been shown not to alter CBF²⁹ or to increase³⁰ or decrease^{31,32} CBF. These conflicting results may be caused by differences in the species used, in the bypass flow rate, and in the duration of ECMO before CBF was measured. However, because many

physiologic conditions change during ECMO induction, the cause of hemodynamic changes will be multifactorial.

Some factors could influence cerebral hemodynamics during induction of ECMO. First, changes in arterial blood gas values are probably not responsible for the increases in CBV and CBF found in our study. No changes in arterial PCO₂ and acid-base balance were found. Increased arterial PO₂ would be expected to result in decreases of CBF and CBV. In the selected regression models, the inverse relation between Δ ctHb, as a representation of Δ CBV, and Δ tcPO₂ was confirmed. On the other hand, the increases of CBV and MBFV may also be caused by reactive hyperperfusion due to prolonged hypoxemia before ECMO. In hypoxemic newborn piglets, significant cerebral hyperperfusion has been shown after restoration of normoxemia.³³

Second, the regression models showed a clear relation between Δ MABP and Δ ctHb as a representation of Δ CBV. Changes of CBV following changes of MABP are considered to result from disturbed autoregulation,²⁶ which occurs in distressed newborn infants.³⁴ However, impairment of cerebral autoregulation occurs in normoxemic newborn lambs undergoing venoarterial ECMO.³⁵ Disruption of the blood flow-metabolism couple in the brain occurs in pigs undergoing normothermic nonpulsatile cardiopulmonary bypass, indicating "luxury perfusion syndrome," but not in those undergoing pulsatile cardiopulmonary bypass.³⁶ It seems, therefore, that the ECMO procedure itself is a potential cause of impaired autoregulation. It introduces a reduced arterial pulsatility caused by the use of a roller pump, as reflected by the decreased PI in our patients. This might impair the autoregulatory function, as it has been postulated that the pulse pressure may participate in autoregulation of capillary beds.³⁶

Third, significant hemodilution during induction of ECMO will result in a decrease of arterial O₂ content. Therefore, CBF will increase to maintain cerebral O₂ delivery.¹⁸

It seems that these changes in cerebral hemodynamics after starting ECMO result from both the ECMO procedure itself and the prolonged pre-ECMO hypoxemia. Because fluctuations of cerebral hemodynamics in severely distressed infants might be harmful for the brain, they must be avoided. Further studies are necessary to identify all of the factors responsible for the perturbation of cerebral hemodynamics during ECMO.

In conclusion, NIRS is a valuable tool for studying cerebral oxygenation and hemodynamics during induction of ECMO. We found alterations in cerebral oxygenation reflecting increased O₂ extraction after carotid ligation, but not after subsequent jugular ligation. Despite the increase in the cerebral O₂ supply after starting ECMO, intracellular O₂ availability was unchanged, probably reflecting sufficient preservation of cerebral intracellular oxygenation and energy metabolism in the pre-ECMO period despite prolonged hypoxemia. The observed increases in CBV and cerebral MBFV may result from the following: (1) reactive hyperperfusion, (2) loss of autoregulation

TABLE 3. Changes in Mean Blood Flow Velocity (MBFV) and Pulsatility Index (PI) Values at 90 Minutes After Start of Extracorporeal Membrane Oxygenation (ECMO) (n = 18)*

	MBFV		PI	
	Absolute Precannulation Values, cm/s	Changes 60 min After Starting ECMO, %	Absolute Precannulation Values, cm/s	Changes 60 min After Starting ECMO, %
Internal carotid artery				
Right	21.0 (17.0 to 27.0)	57.47†‡ (34.09 to 103.70)	1.92 (1.25 to 2.56)	-68.37† (-70.53 to -44.33)
Left	20.0 (16.0 to 26.0)	100.61† (52.49 to 166.67)	1.88 (1.28 to 2.44)	-59.60† (-72.60 to -41.18)
Middle cerebral artery				
Right	23.5 (20.0 to 35.0)	18.57 (-14.29 to 44.00)	1.83 (1.50 to 2.65)	-65.92† (-75.12 to -59.24)
Left	23.5 (21.0 to 31.0)	29.26† (5.56 to 42.86)	1.59 (1.13 to 1.87)	-51.46† (-66.06 to -33.63)

* Values are median (interquartile range).

† Significant changes ($P \leq .01$).

‡ Reversed flow.

because of prolonged hypoxemia before ECMO and/or decreased arterial pulsatility, or (3) compensation for hemodilution related to the ECMO procedure.

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REFERENCES

- Short BL, Miller MK, Anderson KD. Extracorporeal membrane oxygenation in the management of respiratory failure in the newborn. *Clin Perinatol.* 1987;14:737-748
- Stolar CJH, Snedecor SM, Bartlett RH. Extracorporeal membrane oxygenation and neonatal respiratory failure: experience from the Extracorporeal Life Support Organization. *J Pediatr Surg.* 1991;26:563-571
- Taylor GA, Short BL, Fitz CR. Imaging of cerebrovascular injury in infants treated with extracorporeal membrane oxygenation. *J Pediatr.* 1989;114:635-639
- Wyatt JS, Cope M, Delpy DT, Wray S, Reynolds EOR. Quantification of cerebral oxygenation and haemodynamics in sick newborn infants by near infrared spectrophotometry. *Lancet.* 1986;ii:1063-1066
- Thorniley MS, Livera LN, Wickramasinghe YABD, Spencer SA, Rolfe P. The non-invasive monitoring of cerebral tissue oxygenation. *Adv Exp Med Biol.* 1990;277:323-334
- Liem KD, Hopman JCW, Kollée LAA, Oeseburg B. Assessment of cerebral oxygenation and hemodynamics by near infrared spectrophotometry during induction of ECMO: preliminary results. *Adv Exp Med Biol.* 1992;317:841-846
- Liem KD, Hopman JCW, Kollée LAA, Oeseburg B. Near infrared spectrophotometric assessment of cerebral oxygenation during induction of ECMO (abstract). *J Perinat Med.* 1992;20(Suppl 1):131
- Jöbsis FF. Noninvasive infrared monitoring of cerebral and myocardial oxygen sufficiency and circulatory parameters. *Science.* 1977;198:1264-1267
- Liem KD, Hopman JCW, Kollée LAA, Oeseburg B. Effects of repeated indomethacin administration on cerebral oxygenation and haemodynamics in preterm infants: combined near infrared spectrophotometry and Doppler ultrasound study. *Eur J Pediatr.* 1994;153:504-509
- Van der Zee P, Cope M, Arridge SR, et al. Experimentally measured optical pathlengths for the adult head, calf and forearm and the head of the newborn infant as a function of inter optode spacing. *Adv Exp Med Biol.* 1992;316:143-153
- Wyatt JS, Cope M, Delpy DT, et al. Measurement of optical pathlength for cerebral near-infrared spectroscopy in newborn infants. *Dev Neurosci.* 1990;12:140-144
- Wickramasinghe Y, Rolfe P. Modified NIR coefficients taking into account the wavelength dependence of optical pathlength. In: Bancroft J, ed. *Newsletter EC Concerted Action Near Infrared Spectrophotometry & Imaging of Biological Tissues.* Issue 2. Stoke on Trent;1993:5
- Jöbsis-Vandervliet FF. Near infrared monitoring of cerebral cytochrome c oxidase: past and present (and future?). In: Lafeber HN, Aarnoudse JG, Jongsma HW, eds. *Fetal and Neonatal Physiological Measurements. Proceedings of the 4th International Conference on Fetal and Neonatal Physiological Measurements.* Amsterdam: Elsevier Science Publishers; 1991: 41-55
- Raju TNK, Kim SY, Meller JL, Srinivasan G, Ghai V, Reyes H. Circle of Willis blood flow velocity and flow direction after common carotid artery ligation for neonatal extra corporeal membrane oxygenation. *Pediatrics.* 1989;83:343-347
- Koziol JA, Maxwell DA. A distribution-free test for paired growth curve analysis with application to an animal tumour immunotherapy experiment. *Stat Med.* 1982;1:83-89
- Lammertsma AA, Brooks DJ, Beaney RP, et al. In vivo measurement of regional cerebral haematocrit using positron emission tomography. *J Cereb Blood Flow Metab.* 1984;4:317-322
- Wyatt JS, Cope M, Delpy DT, et al. Quantification of cerebral blood volume in human infants by near-infrared spectroscopy. *J Appl Physiol.* 1990;68:1086-1091
- Jones MD, Traystman RJ. Cerebral oxygenation of the fetus, newborn, and adult. *Semin Perinatol.* 1984;8:205-216
- Alpers BJ, Barry RG, Paddison RM. Anatomical studies of the circle of Willis in normal brain. *AMA Arch Neurol Psychiatry.* 1959;81:409-418
- Schumacher RE, Barks JDE, Johnston MV, et al. Right-sided brain lesions in infants following extracorporeal membrane oxygenation. *Pediatrics.* 1988;82:155-161
- Taylor GA, Short BL, Glass P, Ichord R. Cerebral hemodynamics in infants undergoing extracorporeal membrane oxygenation: further observations. *Radiology.* 1988;168:163-167
- Matsumoto JS, Babcock DS, Brody AS, Weiss RG, Ryckman FG, Hiyama D. Right common carotid artery ligation for extracorporeal membrane oxygenation: cerebral blood flow velocity measurement with Doppler duplex US. *Radiology.* 1990;175:757-760
- Cowan F, Thoresen M. Ultrasound study of the cranial venous system in the human newborn infant and the adult. *Acta Physiol Scand.* 1983; 117:131-137
- Taylor GA, Walker LK. Intracranial venous system in newborns treated with extracorporeal membrane oxygenation: Doppler US evaluation after ligation of the right jugular vein. *Radiology.* 1992;183:453-456
- Pryds O, Greisen G, Skov LL, Friis-Hansen B. Carbon dioxide-related changes in cerebral blood volume and cerebral blood flow in mechanically ventilated preterm neonates: comparison of near infrared spectrophotometry and ¹³³Xenon clearance. *Pediatr Res.* 1990;27:445-449
- Mchedlishvili G. *Arterial Behaviour and Blood Circulation in the Brain.* New York: Plenum; 1986:56-71
- Greisen G, Johansen K, Ellison PH, Fredriksen PS, Mali J, Friis-Hansen B. Cerebral blood flow in the newborn infant: comparison of Doppler ultrasound and ¹³³Xenon clearance. *J Pediatr.* 1984;104:411-418
- Risberg J, Ancrì D, Ingvar DH. Correlation between cerebral blood volume and cerebral blood flow in the cat. *Exp Brain Res.* 1969;8:321-326
- Short BL, Walker LK, Gleason CA, Jones MD, Traystman RJ. Effect of

- extracorporeal membrane oxygenation on cerebral blood flow and cerebral oxygen metabolism in newborn sheep. *Pediatr Res.* 1990;28:50-53
30. Smith HG, Whittlesey GC, Kundu SK, et al. Regional blood flow during extracorporeal membrane oxygenation in lambs. *ASAIO Trans.* 1989;35:657-660
31. Nowlen TT, Salley SO, Whittlesey GC, et al. Regional blood flow distribution during extracorporeal membrane oxygenation in rabbits. *J Thorac Cardiovasc Surg.* 1989;98:1138-1143
32. Rosenberg AA, Kinsella JP. Effect of extracorporeal membrane oxygenation on cerebral hemodynamics in newborn lambs. *Crit Care Med.* 1992;20:1575-1581
33. Odden JP, Stiris T, Hansen TWR, Bratlid D. Cerebral blood flow during experimental hypoxaemia and ischaemia in the newborn piglet. *Acta Paediatr Scand Suppl.* 1989;360:13-19
34. Lou HC, Lassen NA, Friis-Hansen B. Impaired autoregulation of cerebral blood flow in the distressed newborn infant. *J Pediatr.* 1979;94:118-121
35. Short BL, Walker LK, Bender KS, Traystman RJ. Impairment of cerebral autoregulation during extracorporeal membrane oxygenation in newborn lambs. *Pediatr Res.* 1993;33:289-294
36. Andersen K, Waaben J, Husum B, et al. Nonpulsatile cardiopulmonary bypass disrupts the flow-metabolism couple in the brain. *J Thorac Cardiovasc Surg.* 1985;90:570-579

NOTICE

Crigler-Najjar Syndrome

A Small Research Conference on this syndrome is to be held in 1996 to discuss new therapies which *might* be available.

I would appreciate hearing from physicians caring for such patients in order to inform them of the meeting and make the proceedings available to them. A newsletter and registry of individuals interested in this topic will be established if there is sufficient interest. **Contact:** Jerold F. Lucey, MD, FAAP, Prof. of Pediatrics, Editor of *Pediatrics*, Medical Center Hospital of Vermont (Fletcher Allen Health Care), Burlington, VT 05401. Telephone: (802) 862-8778.