

Disturbance of Cerebral Oxygenation and Hemodynamics Related to the Opening of the Bypass Bridge during Venous-Arterial Extracorporeal Membrane Oxygenation¹

K. D. LIEM, L. A. A. KOLLÉE, J. H. G. M. KLAESSENS, W. B. GEVEN, C. FESTEN,
A. F. J. DE HAAN, AND B. OESEBURG

ECMO Research Group, Department of Pediatrics [K.D.L., L.A.A.K., J.H.G.M.K., W.B.G.], Pediatric Surgery [C.F.], Medical Statistics [A.F.J.D.H.], and Physiology [B.O.], University Hospital and Faculty of Medical Sciences, University of Nijmegen, Nijmegen, The Netherlands

ABSTRACT

The objective of this study was to investigate changes of cerebral oxygenation and hemodynamics related to opening of the bypass bridge during venous-arterial extracorporeal membrane oxygenation (ECMO). Ten newborn infants and 12 piglets were studied during opening of the bridge for 10 and 1 s, respectively. Changes in cerebral concentration of oxyhemoglobin (*cO₂Hb*), deoxyhemoglobin (*cHHb*), (oxidized-reduced) cytochrome *aa₃* (*cCyt.aa₃*), and blood volume (CBV) were continuously measured by near infrared spectrophotometry. Heart rate, arterial *O₂* saturation (*saO₂*), and mean arterial blood pressure (MABP) were measured simultaneously. In the piglets, central venous pressure (CVP), intracranial pressure (ICP), and left common carotid artery blood flow (CaBF) were also measured. Opening of the bridge for 10 s in the infants resulted in a significant decrease in MABP, *saO₂*, and *cO₂Hb*, whereas *cHHb* increased. CBV did not change significantly. In piglets biphasic changes were observed for MABP, CaBF, *cO₂Hb*, and CBV, showing an initial decrease followed by a smaller increase. *cHHb* and CVP showed reverse biphasic changes. ICP increased but *saO₂* was unchanged. In all cases heart rate and *cCyt.aa₃* did not change significantly. Opening of the bridge for 1 s resulted in minor changes in only a few variables. In conclusion, opening of the

bridge resulted in a decrease of CBV and cerebral *O₂* supply due to a decrease of cerebral blood flow, followed by a compensatory increase of cerebral *O₂* extraction and vasodilatation. The return of oxygenated blood after reclosing resulted in an increase of CBV with overcompensation of cerebral *O₂* supply. (*Pediatr Res* 38: 124–129, 1995)

Abbreviations

ECMO, extracorporeal membrane oxygenation
NIRS, near infrared spectrophotometry
cO₂Hb, oxyhemoglobin concentration²
cHHb, deoxyhemoglobin concentration²
ctHb, total Hb concentration²
cCyt.aa₃, (oxidized-reduced) cytochrome *aa₃* concentration
CBV, cerebral blood volume
CBF, cerebral blood flow
CaBF, mean carotid blood flow
saO₂, arterial *O₂* saturation
MABP, mean arterial blood pressure
CVP, central venous pressure
ICP, intracranial pressure

ECMO improves the survival rate of newborn infants with severe respiratory failure, who do not respond to conventional treatment (1, 2). In many short-term follow up studies the handicap rate among survivors was reported to be about 20%

(3, 4). Cerebrovascular injury is one of the important predictors of poor neurodevelopmental outcome (3).

In the ECMO circuit a bypass bridge is placed between the arterial and the venous tubing to allow continuation of blood circulation in the ECMO system during an emergency when the patient is taken off ECMO by clamping both cannulae (5, 6). During the ECMO run, the bridge is clamped, but to prevent clot formation from prolonged blood stasis in the bridge, brief opening of the bridge every 15 min is part of routine management. However, opening of the bridge results in arterial-venous shunting in the ECMO circuit which might disturb the blood circulation

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Correspondence: K. D. Liem, Department of Pediatrics, University Hospital Nijmegen, P.O. Box 9101, 6500 HB Nijmegen, The Netherlands.

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and O₂ supply to the brain. Using NIRS, the influence of bypass bridge opening on cerebral oxygenation and hemodynamics was investigated in newborn infants and in piglets.

METHODS

Newborn infants. Ten newborn infants (gestational age, 35.1–41.6 wk; birth weight, 2100–4330 g; eight boys and two girls) who required ECMO treatment were studied after informed parental consent was given. The study was approved by the University Hospital ethics committee. All infants met the established ECMO selection criteria (1), which include cerebral ultrasound investigation. So, infants with cerebral hemorrhage or cerebral malformation would have been excluded. The underlying diseases were congenital diaphragmatic hernia ($n = 4$), meconium aspiration syndrome ($n = 2$), and persistent pulmonary hypertension due to other causes ($n = 4$). Before cannulation the infants were anesthetized using Fentanyl (0.01 mg/kg) (Janssen, Tilburg, The Netherlands) and midazolam (0.1 mg/kg). All infants were already paralyzed with pancuronium (0.01–0.02 mg/kg/h) and treated with vasoactive drugs (dopamine and/or dobutamine, 5–10 μ g/kg/h). During ECMO the infants were mechanically ventilated (Babylog 8000, Dräger, Lübeck, Germany) at a low level for pressure (20–25 mbar), rate (16 breaths/min), and inspiratory O₂ fraction (0.30). Medication prescribed before ECMO was continued during the measurement period.

Heart rate and (umbilical) MABP were continuously monitored (Sirecust 404N, Siemens, Erlangen, Germany). Foot arterial O₂ saturation (saO₂) was also continuously measured by pulse oximetry (N 200, Nellcor Inc., Hayward, CA).

Piglets. Twelve female piglets (age 2–3 wk, weight 7.6–8.5 kg) were obtained from a local farm. The piglet was selected as the animal model because of its closer physiologic resemblance to the human infant, easy availability, and low cost (7). For sedation, a mixture of droperidol and Fentanyl (0.25 mg/kg and 0.005 mg/kg, respectively) was administered intramuscularly. After 30 min anesthesia was induced by i.v. midazolam (1.5 mg/kg), atropine (0, 25 mg), and Fentanyl (0.2 mg/kg). During artificial ventilation (Babylog 8000, Dräger), anesthesia was maintained using i.v. Fentanyl (0.2 mg/kg/h), midazolam (0.4 mg/kg/h), and droperidol (0.1 mg/kg/h). The piglets were paralyzed with pancuronium (loading dose 0.2 mg/kg, maintaining dose 0.15 mg/kg/h). The ventilator settings were adjusted to maintain paCO₂ between 30 and 40 mm Hg (4–5.3 kPa) and paO₂ between 75 and 100 mm Hg (10–13.3 kPa). Rectal temperature was monitored and maintained between 38 and 39°C with a servo-controlled heating mattress.

Catheters were placed in the abdominal aorta through a femoral artery and in the inferior vena cava near the right atrium via a femoral vein for continuous monitoring of MABP (HP 78206C, Hewlett Packard, Boeblingen, Germany) and CVP (HP 78205C, Hewlett Packard, Boeblingen, Germany). Through the other femoral artery a fiberoptic oximeter catheter (Spectracath STP 7.5 F, Viggo Spectramed, Oxnard, CA) was inserted into the abdominal aorta for on-line continuous monitoring of saO₂ (HemoprO₂ SP1455, Viggo Spectramed, Oxnard, CA). Mean blood flow in the left common carotid artery

(CaBF) was continuously recorded by an electromagnetic flowmeter (Scalar MDL 1401, Scalar Medical, Delft, The Netherlands) using a 2.5-mm diameter probe. Changes in CaBF reflect changes in CBF (8). After neck incision the cisterna magna was punctured with a hollow needle through the foramen magnum, and a catheter was placed through the needle into the cisterna magna for continuous monitoring of ICP (HP 78205C, Hewlett Packard, Boeblingen, Germany). The needle was withdrawn after successful positioning of the catheter, as shown by a pulsatile signal on the monitor.

Six piglets were put on ECMO during normoxemic condition. The other six piglets were put on ECMO after being hypoxemic (saO₂ < 80%) for at least 2 h due to ventilator FiO₂ between 0.16 and 0.18.

NIRS. The NIRS equipment used was developed by the Department of Biomedical Engineering and Medical Physics, University of Keele (UK) and produced by Radiometer (Copenhagen, Denmark) (9). This method is based on spectrophotometric measurement of changes in the absorption properties of Hb and cytochrome aa₃ in the near infrared region, depending on their oxygenation state (10). Details of our NIRS measurement procedure have been described earlier (11). Briefly, near infrared light at three wavelengths (904, 845, and 775 nm) was transmitted through the skull by fiberoptic bundles. Using the described algorithm, concentration changes of oxyhemoglobin (Δ cO₂Hb), deoxyhemoglobin (Δ cHHb), and (oxidized-reduced) cytochrome aa₃ (Δ cCyt.aa₃) were calculated from changes in absorption of near infrared light at these three wavelengths. The transmitting and receiving optodes were fixed to the skull as previously described (12). In the infants they were placed at a relative angle of approximately 90°, one at the anterior fontanelle, the other at the right parieto-temporal region. In piglets each optode was positioned between the midline of the skull and the ear. Interoptode spacing was >2.5 cm, to ensure a constant path length multiplying factor (13), which has been stated to be 4.39 times the interoptode spacing (14). As the optical path length is wavelength-dependent, some modification of the algorithm has been made (15). Using the obtained optical path length and a value of 1.05 for brain-specific mass, the concentration changes are expressed in micromoles/100 g. Δ cO₂Hb and Δ cHHb reflect changes in cerebral O₂ supply, whereas Δ cCyt.aa₃ reflects changes in cerebral O₂ availability (16). Changes in concentration of total Hb (Δ ctHb) were calculated as the sum of Δ cO₂Hb and Δ cHHb. Changes in cerebral blood volume (Δ CBV), expressed in milliliters/100 g, were calculated from the formula Δ CBV = (4· Δ ctHb)/(0.69·cHb), where cHb = arterial Hb concentration in millimoles/L, 0.69 = cerebral-arterial hematocrit ratio (17), and 4 = correction factor, because ctHb is calculated from changes in light absorption using extinction coefficient based on the tetraheme molecule, whereas cHb determination is based on the monoheme molecule.

Experimental procedure. After cannulation of the right common carotid artery and the internal jugular vein (in piglets the external jugular vein was used) standard veno-arterial ECMO was performed (1). After starting ECMO the flow rate was increased gradually over several minutes until a level (ranging from 140 to 205 mL/kg/h in the infants and from 65

to 100 mL/kg/h in the piglets) was reached, which was sufficient to maintain saO_2 between 95 and 100%. Approximately 1 h after the start of ECMO and stabilization of all variables, the bypass bridge was opened for 10 s. After restabilization of the measured variables, the bypass bridge was opened again for just 1 s, because in current clinical practice the period during which the bridge is opened ranges from 1 to 10 s. Due to expected changes in cerebral oxygenation and hemodynamics, a longer opening time than 10 s might expose the newborn to unnecessary risk. To imitate the clinical situation we used the same opening time of the bridge in the piglets and did not wait till a steady state was reached during opening of the bridge. During the experiments all variables were measured by a sampling rate of 1 Hz. Due to technical problems, the data of a 1-s bridge opening in one piglet were not available. Measurement of CaBF failed in another piglet.

Data analysis. Before analysis, the data of CVP and ICP were filtered with a 0.3-Hz low pass filter to reduce signal noise caused by breathing movements. For each variable the mean and SD value were calculated from a 30-s period before opening of the bypass bridge. The beginning of MABP change was considered to represent the actual beginning of the bridge opening ($t = 0$). The mean values were the base levels for the corresponding signal. The analysis searched for the first minimum and maximum change within 120 s. The search for the first minimum started if the signal exceeded the base level more than -2 SD for more than 3 s and continued until the signal exceeded a level more than 2 SD above the local minimum for more than 3 s. The first maximum was found in a similar way. Minimum and maximum changes were calculated as the difference between this local minimum or maximum and its base level. When no peak change was found a value of zero was taken. The results were statistically analyzed by performing the Wilcoxon signed rank test and the level of significance was chosen at 0.01 to correct for multiple testing (Bonferoni correction).

RESULTS

Newborn infants. Recording of important variables in an infant during opening of the bridge for 10 s is shown in Figure 1. The results of the calculation are presented in Tables 1 and 2. Opening of the bypass bridge for 10 s was followed by a significant decrease in MABP, cO_2Hb , and saO_2 and an increase in $cHHb$. CBV showed changes suggestive of a biphasic course, showing an initial decrease followed by a secondary increase, but these changes were not large enough to reach statistical significance. The peak change of the NIRS variables occurred at the same time interval as that of MABP. The negative peak change of saO_2 occurred after that of MABP. After opening of the bridge for 1 s, only a significant decrease of cO_2Hb and MABP and a increase of $cHHb$ were observed. As expected, the values of these peak changes were smaller than after a 10-s opening of the bridge. Heart rate and $cCyt.a_3$ were unchanged in both interventions and therefore are not shown in the tables.

Piglets. Recording of important variables in a piglet during opening of the bridge for 10 s are shown in Figure 2. Inasmuch as there was no significant difference in the response between

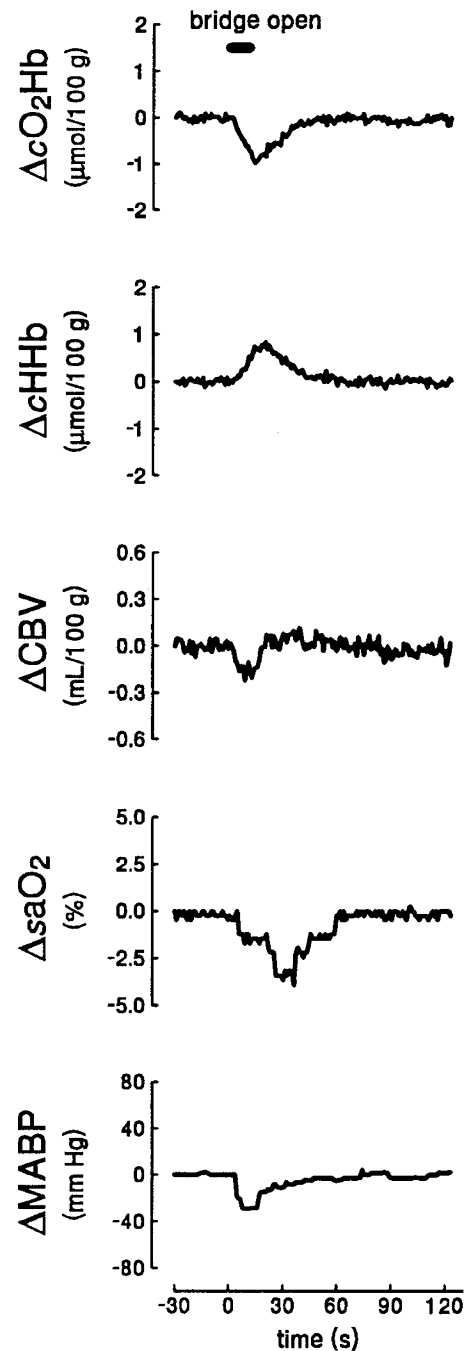


Figure 1. Registration of cO_2Hb , $cHHb$, $ctHb$, saO_2 , and MABP during opening of the bypass bridge for 10 s in an infant (sampling frequency, 1 Hz).

hypoxic and normoxic piglets, they were considered as one group. The response was in the same direction as that in the infant experiment, but the magnitude of the changes was different (Tables 3 and 4). However, a biphasic response after a 10-s opening of the bypass bridge was observed for MABP, CaBF, cO_2Hb , and CBV, showing an initial decrease followed by a smaller increase. Reverse biphasic response was observed for $cHHb$ and CVP. The first peak change of these variables occurred at the same time interval. However, the second peak change of cO_2Hb and $cHHb$ occurred significantly later than that of CBV. In most piglets ICP showed a biphasic response (Fig. 2). However, only the second (positive) peak change was

Table 1. Changes during opening of the bypass bridge for 10 s in 10 infants during ECMO

	Absolute value before opening	First peak change	Interval time (s)	Second peak change	Interval time (s)
Δ MABP (mm Hg)	53.1 (40.0, 64.7)	-14.5* (-29.1, -2.0)	11 (5, 15)	0.0 (0.0, 2.2)	64 (42, 85)
Δ saO ₂ (%)	94.3 (90.9, 100.0)	-7.9* (-19.8, -3.0)	20 (12, 36)	0.0 (0.0, 0.0)	—
Δ cO ₂ Hb (μ mol/100 g)	Not available	-0.74* (-1.14, -0.42)	14 (11, 20)	0.04 (0.00, 0.33)	70 (45, 81)
Δ cHHb (μ mol/100 g)	Not available	0.62* (0.46, 1.23)	16 (13, 22)	0.00 (-0.20, 0.00)	72 (47, 88)
Δ CBV (mL/100 g)	Not available	-0.19 (-0.33, 0.14)	10 (5, 21)	0.10 (-0.06, 0.18)	30 (19, 108)

Values are median (range).

* $p < 0.01$.

Table 2. Changes during opening of the bypass bridge for 1 s in 10 infants during ECMO

	Absolute value before opening	First peak change	Interval time (s)	Second peak change	Interval time (s)
Δ MABP (mm Hg)	54.0 (40.0, 74.3)	-2.7 (-4.6, -1.8)	8 (4, 15)	0.0 (0.0, 0.0)	—
Δ saO ₂ (%)	96.8 (89.5, 100.0)	-0.0 (-3.1, 1.5)	22 (7, 86)	0.0 (-1.4, 2.0)	53 (17, 89)
Δ cO ₂ Hb (μ mol/100 g)	Not available	-0.11 (-0.16, 0.00)	7 (3, 9)	0.05 (0.00, 0.23)	49 (15, 113)
Δ cHHb (μ mol/100 g)	Not available	0.10 (-0.10, 0.13)	7 (5, 16)	0.00 (-0.19, 0.00)	72 (54, 91)
Δ CBV (mL/100 g)	Not available	-0.00 (-0.14, 0.12)	34 (3, 110)	0.00 (0.00, 0.10)	12 (12, 12)

Values are median (range).

statistically significant. After opening of the bridge for 1 s, only a single peak change was observed for cHHb, CaBF, MABP, and CVP. saO₂, heart rate, and cCyt.aa₃ did not change in either intervention. They are not shown in the tables.

DISCUSSION

We showed that opening of the ECMO bypass bridge results in significant changes in cerebral oxygenation and hemodynamics. Because after a 10-s opening no steady state occurs, it is impossible to separate the variation in the magnitude of the responses from the rapidity of responses. However, the observed changes can be explained as follows (Fig. 3). Opening of the bridge results in shunting of arterial blood from the oxygenator through the open bypass bridge to the low pressure venous part of the circuit. Because of higher aortic blood pressure, a retrograde blood flow from the arterial cannula into the bypass bridge will occur, resulting in MABP decrease. Simultaneously an initial decrease of CBV was also observed, although this was less clear in the infants. Theoretically a CBV decrease is caused by decreased CBF or increased venous outflow (18). Decreased rather than increased cerebral venous outflow seems to occur, as in piglets CVP increased. Therefore the decrease of CBV can be explained by a larger decrease of CBF than of cerebral venous outflow. Decreased CaBF in our piglets reflects also decreased CBF (8). A positive relationship between CBF and CBV has been described (19). These CBF changes seemed to be related to MABP changes and might be due to disturbed autoregulation during ECMO (20, 21). There

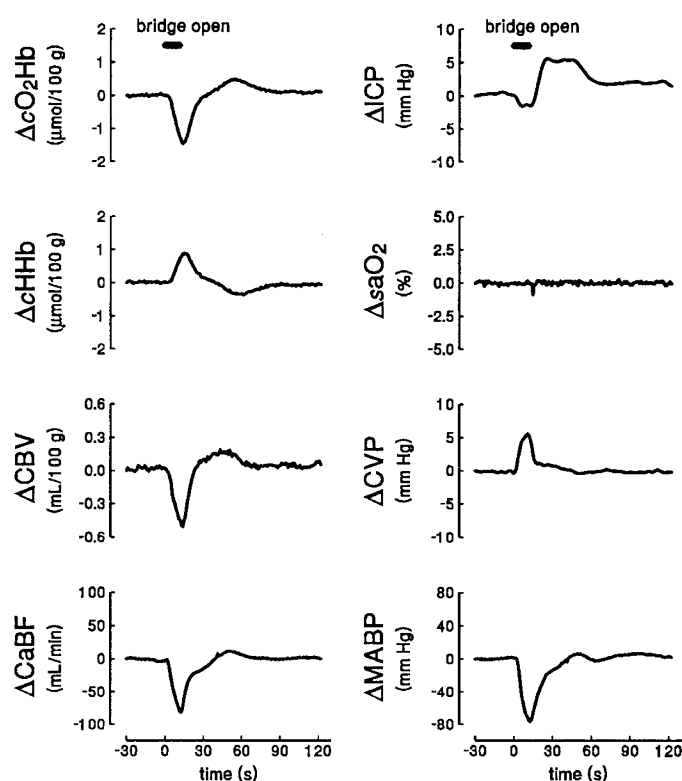


Figure 2. Registration of cO₂Hb, cHHb, cHb, CaBF, ICP, CVP, saO₂, and MABP during opening of the bypass bridge for 10 s in a piglet (sampling frequency, 1 Hz).

Table 3. Changes during opening of the bypass bridge for 10 s in 12 piglets during ECMO

	Absolute value before opening	First peak change	Interval time (s)	Second peak change	Interval time (s)
Δ MABP (mm Hg)	113.7 (79.0, 135.7)	-37.6** (-76.9, -26.0)	12 (9, 14)	2.5* (0.0, 8.9)	34 (19, 76)
Δ CVP (mm Hg)	6.7 (4.9, 10.5)	3.6** (1.9, 7.8)	8 (6, 14)	-0.6* (-1.6, 0.0)	24 (16, 62)
Δ saO ₂ (%)	99.3 (86.1, 99.4)	0.0 (-2.9, 1.7)	16 (8, 39)	0.0 (-6.3, 0.0)	28 (22, 33)
Δ ICP (mm Hg)	16.0 (10.5, 21.2)	-1.8 (-4.1, 2.8)	7 (4, 14)	4.7* (-0.8, 12.5)	19 (12, 80)
Δ CaBF† (mL/min)	123.8 (92.2, 200.7)	-37.3** (-80.3, -30.8)	11 (9, 13)	8.2* (0.0, 18.9)	24 (19, 50)
Δ cO ₂ Hb (μ mol/100 g)	Not available	-0.65** (-1.48, -0.42)	12 (7, 22)	0.16** (0.00, 0.50)	53 (15, 68)
Δ cHHb (μ mol/100 g)	Not available	0.50** (0.24, 0.87)	13 (9, 22)	-0.14* (-0.37, 0.00)	60 (53, 68)
Δ CBV (mL/100 g)	Not available	-0.24** (-0.52, -0.14)	10 (7, 14)	0.13** (0.06, 0.22)	20 (15, 51)

Values are median (range).

* $p < 0.01$.

** $p < 0.001$.

† $n = 11$.

Table 4. Changes during opening of the bypass bridge for 1 s in 11 piglets during ECMO

	Absolute value before opening	First peak change	Interval time (s)	Second peak change	Interval time (s)
Δ MABP (mm Hg)	105.6 (69.2, 127.9)	-11.7** (-16.9, -6.7)	5 (5, 7)	2.0 (0.0, 3.6)	35 (14, 87)
Δ CVP (mm Hg)	6.4 (4.7, 11.1)	0.9* (-0.8, 2.1)	4 (2, 33)	0.0 (-1.3, 0.0)	20 (15, 23)
Δ saO ₂ (%)	99.3 (94.8, 99.4)	0.0 (-1.7, 0.0)	68 (10, 98)	0.0 (0.0, 0.0)	—
Δ ICP (mm Hg)	13.7 (11.4, 18.7)	-0.6 (-2.2, 2.0)	8 (3, 45)	0.7 (-1.7, 4.2)	13 (8, 42)
Δ CaBF† (mL/min)	126.3 (91.8, 162.4)	-12.4** (-17.4, -8.3)	5 (4, 7)	1.6 (0.0, 5.8)	63 (15, 103)
Δ cO ₂ Hb (μ mol/100 g)	Not available	-0.14 (-0.22, 0.15)	8 (5, 63)	0.00 (0.00, 0.20)	56 (48, 67)
Δ cHHb (μ mol/100 g)	Not available	0.09* (0.00, 0.20)	10 (6, 31)	0.00 (-0.15, 0.00)	50 (17, 59)
Δ CBV (mL/100 g)	Not available	-0.08 (-0.16, 0.16)	12 (5, 82)	0.00 (0.00, 0.07)	41 (17, 58)

Values are median (range).

* $p < 0.01$.

** $p < 0.001$.

† $n = 10$.

is some evidence that the autoregulatory response after blood pressure change occurs with a delay of a few seconds (22). Due to decreased CBF, O₂ supply to the brain will be reduced, as reflected by decreased cO₂Hb. This will be compensated for by increased O₂ extraction, as reflected by the initial increase of cHHb, as well as by arteriolar vasodilatation, as reflected by the secondary increase of CBV and the delayed increase of ICP. The secondary increase of cO₂Hb, which occurred later than CBV increase, can be explained by the return of oxygenated blood to the dilated cerebral vascular bed after closing the bridge. This will also result in decreased O₂ extraction, as reflected by the secondary decrease of cHHb. The initial increase of cHHb could also be explained by decreased cerebral venous outflow, because CVP is increased due to relative obstruction of venous blood flow in the venous tubing by

arterial-venous shunting of blood through the bridge. However, occurrence of retrograde flow of arterial blood through the venous tubing to the right atrium cannot be excluded. Further investigation is needed to clarify the flow changes in each part of the circuit during opening of the bypass bridge.

The lack of biphasic responses in the newborn infants might be caused by decrease of vascular reactivity due to vasoactive agents, which are usually used before starting ECMO. In the piglets these agents were not used, permitting complete counterregulation after closing the bridge.

As the piglet lungs were normal, the animals were able to maintain saO₂, despite a significant reduction of oxygenated blood supply during opening of the bypass bridge. In contrast, the poor pulmonary function of the infants results in inability to maintain saO₂ during opening of the bridge. This normally will result in

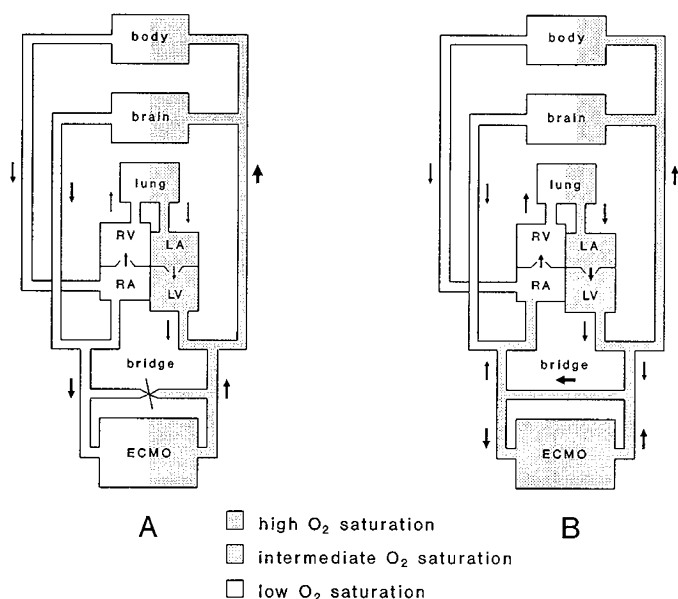


Figure 3. Schematic model of blood flow direction and oxygenation during ECMO in respiratory distressed newborn with closed bypass bridge (A) and presumed changes when the bridge is open (B). RA = right atrium, LA = left atrium, RV = right ventricle, LV = left ventricle.

decrease of cerebral vascular resistance and consequently increase in CBV, which might compensate for the CBV decrease caused by reduction of MABP and explain the less clear effect of bridge opening on CBV in the infants.

The clinical relevance of our findings is unclear, because this is the first report showing evident changes in cerebral circulation and O₂ supply due to bridge opening. It might be harmful for the brain, but this is not supported by the finding of unchanged cCyt.a₃, reflecting unaffected cerebral O₂ availability. However, data on cCyt.a₃ should be interpreted with caution, inasmuch as the value was calculated using an algorithm that is derived from experiments on rat brains after exchange transfusion with fluorocarbon, and therefore results might be affected by noise due to residual Hb after fluorocarbon exchange (19), as well as due to scattering by fluorocarbon which is different from that of erythrocytes. During an average ECMO run of 120-h duration (2), the bridge will be opened manually approximately 480 times with variable duration. It can be speculated that this frequently repeated perturbation of the cerebral circulation might be a risk factor for cerebrovascular injury, an important complication during ECMO (2, 23) and a strong predictor of poor neurodevelopmental outcome (3).

As the bypass bridge is an essential part of the ECMO circuit, an alternative strategy for preventing clot formation should be looked for. An adjustable valve in the bridge allowing a very low but continuous blood flow through the bridge could be designed. Another future option would be the design of a one-way valve in different parts of the ECMO circuit. However, it is not known whether the presence of such valves would result in local turbulence facilitating thrombus formation.

In conclusion, significant changes in cerebral oxygenation and hemodynamics were observed during opening of the bypass bridge during ECMO. The clinical relevance is unclear, but these frequently recurring changes may contribute to cere-

brovascular injury during ECMO. Further study is necessary to determine the best management of the bypass bridge during ECMO.

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