

# Pumpless extracorporeal lung assist – experience with the first 20 cases<sup>☆</sup>

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## Abstract

**Objective:** Long-term extracorporeal lung assist is limited by a significant mechanical blood trauma resulting in bleeding and hemolysis. To reduce the drawbacks of extracorporeal lung assist a new technique has been developed, by which the driving force for the extracorporeal circuit derives from the patients arterio-venous pressure gradient (pumpless extracorporeal lung assist). The aim of this clinical study was to test the feasibility and effectiveness of pumpless extracorporeal lung assist in patients with acute respiratory distress syndrome. **Methods:** Twenty patients (41 ± 16 years) with acute respiratory distress syndrome of various causes and failing respirator therapy were enrolled. The minimum hemodynamic requirements included a cardiac output (CO) > 6 l/min and mean arterial pressure (MAP) > 70 mmHg. Pumpless extracorporeal lung assist was established using a short circuit arterio-venous shunt including a special designed low-resistance membrane oxygenator which was placed between the patients legs. **Results:** At the time of inclusion FiO<sub>2</sub> in all patients was 1.0 (paO<sub>2</sub> 45.9 ± 7 mmHg, paCO<sub>2</sub> 58.9 ± 17 mmHg). After 24 h of pumpless extracorporeal lung assist FiO<sub>2</sub> was reduced to 0.8 ± 0.1. A significant improvement in oxygenation (paO<sub>2</sub> 84.1 ± 21 mmHg, *P* < 0.05) and CO<sub>2</sub> removal (paCO<sub>2</sub> 32.7 ± 5 mmHg, *P* < 0.05) was notable. The mean extracorporeal flow was 2.6 ± 0.6 l/min, which represented approximately 25% of the patients mean CO (10.8 ± 2 l/min). The median assist time was 12 ± 8 (1–32) days. Fifteen out of twenty patients were weaned off pumpless extracorporeal lung assist. Five out of twenty patients died while on the system (four sepsis, one ventricular fibrillation). Three out of twenty patients died after successful weaning on day 8, 30, and 50, respectively. Twelve out of twenty patients were discharged in a healthy state (overall survival 60%). Technical problems included thrombosis of the venous cannula (*n* = 5), thrombus formation within the membrane oxygenator (*n* = 2), membrane oxygenator plasma leakage (*n* = 2), and membrane oxygenator contamination with *Candida albicans*. No bleeding complication was observed. **Conclusion:** Pumpless extracorporeal lung assist is feasible and effective in a selected group of patients with acute respiratory distress syndrome but preserved hemodynamic function. By eliminating the pump and reducing the tubing length blood trauma can be minimized. Being very simple the system entails fewer risks of technical complications and also facilitates nursing care. © 2000 Elsevier Science B.V. All rights reserved.

**Keywords:** Acute respiratory distress syndrome; Pulmonary failure; Extracorporeal lung assist; Pumpless

## 1. Introduction

Despite substantial advancements in the understanding of the acute respiratory distress syndrome (ARDS) which have occurred since its initial description in 1967 [1], the mortality remained above 50% [2,3]. In addition to mechanical ventilation, which is still the mainstay of therapy, a number of novel supportive techniques, including partial liquid ventilation, inhaled nitric oxide, surfactant replacement, and extracorporeal techniques have been applied. Extracorporeal lung assist (ECLA) has been proposed as an invasive

alternative to conventional treatment when oxygenation is not possible by rigorous mechanical ventilation alone. Usually, ECLA is carried out by establishing a venovenous or venoarterial shunt consisting of a roller or centrifugal pump, a membrane lung to exchange oxygen and carbon dioxide, and a heat exchanger to maintain temperature [4]. With the introduction of heparin coated circuits and further refinements in membrane oxygenator (MO) technology the initial high mortality (90%) of ECLA applied in adults [5] could be reduced to 49–53% [6,7]. The most limiting condition is a significant blood trauma during ECLA support leading to hemolysis and coagulation disorders. Moreover, other system-immanent limitations including inflammatory response and specific technical complications made the procedure a high-risk and costly therapy [8].

To reduce the drawbacks of mechanical blood damage

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during prolonged ECLA, a new technique has been developed by which the driving force for the extracorporeal circuit was not a pump but the patient's arteriovenous (AV) pressure gradient. By using a special designed low-resistance MO an artificial AV shunt was established, which provided enough flow within the MO to be as effective as a pump driven system. The aim of our study was to examine the feasibility and effectiveness of pumpless extracorporeal lung assist (pECLA) in a group of patients with ARDS.

## 2. Materials and methods

The study protocol was proven by the local ethical committee. Our analysis contains prospectively collected data on 20 adult patients (median age  $41 \pm 16$  years, range 15–69 years; two females), referred to either the cardiothoracic surgical or medical intensive care unit for treatment of acute lung failure. The clinical definition of ARDS was made using the criteria of the American-European Consensus Conference on ARDS [9]. Patients characteristics and underlying diseases are summarized in Table 1.

Conventional therapy included positive pressure ventilation, high frequency jet ventilation, surfactant replacement, prone position ventilation, and kinetic therapy (Rotorest™). When the patients fulfilled fast or slow entry criteria according to the US ECMO study [5] the further therapeutic strategy was discussed within the interdisciplinary ECLA service of our institution (cardiothoracic surgeon, medical intensive care therapist, perfusionist). Before initiation of pECLA therapy consensus was reached that the patient otherwise would have died and it was confirmed that the pulmonary injury was principally reversible. The hemodynamic situation was evaluated by thermodilution. To assure a sufficient AV flow a cardiac output (CO) of at least 6.0 l/min and a mean arterial pressure (MAP) of at least 70 mmHg were established by an appropriate catecholamine regimen (dopamine up to 20  $\mu\text{g}/\text{kg}/\text{per min}$ , epinephrine up to 4  $\mu\text{g}/\text{kg}/\text{per min}$ , norepinephrine up to 5  $\mu\text{g}/\text{kg}/\text{per min}$ ). Patients suffering from cardiac failure (i.e. low cardiac output syndrome) or severe peripheral circulatory dysregulation (septic shock) were excluded from pECLA therapy. In four cases a formerly installed pump-driven ECLA had to be interrupted due to thrombus formation within the system ( $n = 2$ ) or pump head dysfunction ( $n = 2$ ). Those patients

Table 1  
Patient characteristics and outcome

No.	Age	Diagnosis	Respirator days <sup>a</sup>	pECLA days	Weaning	Outcome <sup>b</sup>	Time of death	Cause of death	Technical problems
1	42	Acute pancreatitis	10	10	Yes	Good			
2	22	Wegeners granulomatosis	5	13	Yes	Died	8 days after ECLA	Sepsis	
3	17	Waterhouse–Fridrichsen syndrome	1	14	Yes	Good			
4	31	T-cell lymphoma	2	13	Yes	Good			Thrombus in MO
5	46	Post perfusion lung	15	7	No	Died	On ECLA	Sepsis	Thrombosis of venus cannula
6	31	Pneumonia ( <i>Pneumocystis carinii</i> )	22	22	Yes	Good			
7	42	Sepsis ( <i>Pneumococci</i> )	18	27	Yes	Good			
8	20	Waterhouse–Fridrichsen syndrome	4	10	No	Died	On ECLA	Sepsis	Thrombosis of venus cannula
9	49	Acute pancreatitis	27	3	Yes	Died	50 days after ECLA	Sepsis	Thrombus in MO
10	69	Bilobal lung resection	9	21	Yes	Died	30 days after ECLA	Kachexia	
11	59	Pneumonia <sup>c</sup>	5	8	Yes	Good			
12	15	Lung contusion	4	8	Yes	Good			
13	19	Pneumonia <sup>c</sup>	13	18	Yes	Good			
14	48	Pneumonia (aspiration)	18	32	Yes	Good			MO contamination ( <i>Candida</i> )
15	40	Sepsis ( <i>Pneumococci</i> )	7	21	No	Died	On ECLA	Ventricular fibrillation	MO plasma leakage
16	43	Pneumonia (Herpes simplex)	15	7	Yes	Good			MO plasma leakage
17	20	Lung contusion	4	8	Yes	Good			Thrombosis of venous cannula
18	32	Pneumonia <sup>c</sup>	1	1	No	Died	On ECLA	Sepsis	
19	60	Pneumonia <sup>c</sup>	11	16	No	Died	On ECLA	Sepsis	Thrombosis of venus cannula
20	60	Bilobal lung resection	1	6	Yes	Good			Thrombosis of venus cannula

<sup>a</sup> Time of ventilator treatment before pECLA institution.

<sup>b</sup> 'Good', hospital discharge finally possible.

<sup>c</sup> Responding agent unknown.

were ‘downgraded’ to pECLA upon confirmation of inclusion criteria. Seven patients suffered from contemporary acute renal failure (ARF) requiring intermittent hemodialysis.

Before insertion of the arterial and venous cannulae the internal diameter of the common femoral artery and vein were estimated by ultrasound. Especially arteriosclerotic plaque formation at the insertion site could be detected. The external diameter of the cannula was chosen approximately 1.0–1.5 mm smaller than the minimal internal diameter of the vessel. We used heparin coated cannulae (BP-FCSA (Jostra Inc., Hirrlingen, Germany), CB 96535 (Medtronic Inc., Minneapolis, MN)) sized from 17–21 F for arterial and 19–21 F for venous cannulation. The cannulae were inserted using Seldinger’s technique with the help of several dilators in increasing diameter. Usually the arterial cannula was placed first for having the opportunity to change to the other leg if difficulties occur (i.e. inability to advance the cannula due to arteriosclerosis or kinking). The venous cannula was then inserted into the opposite leg. After insertion the cannulae were clamped and connected to the prefilled tubing system containing the MO (Quadrox Spezial, Jostra Inc., Hirrlingen, Germany).

This MO prototype is based on the Quadrox™ heparin-coated hollow fibre technology with reduced inner surface area (1.3 m<sup>2</sup>) and optimized blood flow characteristics. By reduction of the blood flow resistance the MO produces a pressure gradient of approximately 15 mmHg between in- and outflow providing a trans MO flow up to 4 l/min. The technical settings of the oxygenator allowed a minimal O<sub>2</sub> transfer of 45 ml/l and a minimal CO<sub>2</sub> transfer of 38 ml/l. The system was primed with 20% human albumin (priming volume approximately 270 ml). As the total extracorporeal length (tip-to-tip) did not exceed 120–130 cm, no heat exchanger was needed. After removal of the clamps an oxygen supply line was connected to the inflow site of the MO with an oxygen flow of 10–12 l/min. A continuous heparin infusion was connected to the arterial cannula to keep the activated clotting time at a level of 130–150 s. A bidirectional ultrasound sensor (Transonic Systems Inc., NY) was placed at the outflow line to determine the extracorporeal flow ( $F_{MO}$ ). A schematic overview of the pECLA components is given in Fig. 1.

During pECLA support the respirator settings were modified to achieve a less aggressive pattern of ventilation aiming in a normalized I:E ratio, a reduced PEEP level, and a reduced maximum airway pressure ( $P_{max}$ ). Pumpless ECLA therapy was discontinued as soon as the patient presented stable (at least 24 h) with an arterial oxygen pressure (paO<sub>2</sub>) of > 80 mmHg at normalized ventilator settings with FiO<sub>2</sub> < 0.5. The cannulae were removed by manual retraction followed by compression of the insertion site. In two cases the arterial cannula was explanted under direct vision including surgical repair of the femoral artery. Serial measurements of MAP, CO, paO<sub>2</sub>, paCO<sub>2</sub>, and  $F_{MO}$  were undertaken throughout the whole period of pECLA therapy

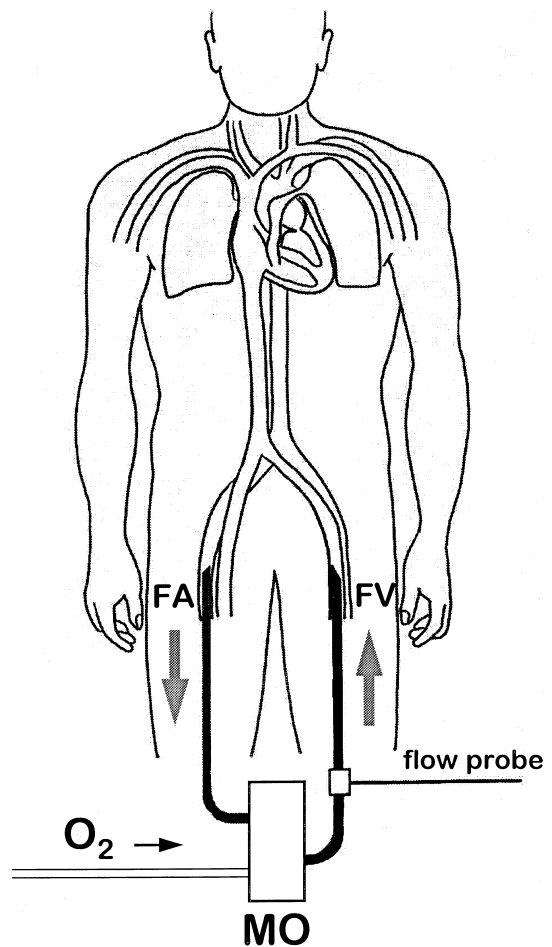


Fig. 1. Simple appearance of pumpless extracorporeal lung assist (pECLA): heparin-coated arteriovenous shunt including membrane oxygenator (MO), which is placed between the patients legs. FA, femoral artery; FV, femoral vein.

and after weaning. Blood gas measurements were made using the ABL 500 (Radiometer Inc., Copenhagen, Denmark).

Values in the text are given as mean  $\pm$  one standard deviation (SD). The values of paO<sub>2</sub>, paCO<sub>2</sub>, FiO<sub>2</sub>, and oxygenation index (paO<sub>2</sub>/FiO<sub>2</sub>) before and throughout pECLA were compared using a paired *t*-test for parametric variables. *P*-values of less than 0.05 were considered statistically significant.

### 3. Results

Before initiation of pECLA the patients had been mechanically ventilated for a period of  $9.6 \pm 7$  days. In all patients the respirator was set at positive pressure ventilation (PEEP  $11.4 \pm 4$  mmHg,  $P_{max}$   $36 \pm 5$  mmHg) using pure oxygen (FiO<sub>2</sub>  $1.0 \pm 0$ ). Blood gas analysis revealed a mean paO<sub>2</sub> of  $45.9 \pm 7$  mmHg and paCO<sub>2</sub> of  $58.9 \pm 17$  mmHg. At the time of pECLA implant the patients presented with stable hemodynamic conditions (MAP

94.1 ± 10 mmHg, CO 10.8 ± 2 l/min). Thus, a mean extracorporeal flow of 2.6 ± 0.6 l/min could be established. After a 24-h course a significant improvement in oxygenation (paO<sub>2</sub> 84.1 ± 21 mmHg at FiO<sub>2</sub> 0.8 ± 0.1; *P* < 0.05) and CO<sub>2</sub> removal (paCO<sub>2</sub> 32.7 ± 5 mmHg; *P* < 0.05) was notable. Fig. 2 demonstrates the improvement of the oxygenation index from pECLA initiation until pECLA stop. The median duration of pECLA therapy was 12 ± 8 days with a range of 1–32 days. The individual clinical course and outcome of each patient is summarized in Table 1. Fifteen out of the 20 patients could be weaned off pECLA. Five patients died while on the system (septic multi-organ failure (*n* = 4), intractable ventricular fibrillation during weaning (*n* = 1)). Two patients died from sepsis after successful weaning (8 and 50 days, respectively). One patient died from kachexia 30 days after weaning. Twelve out of the 20 patients survived the procedure in a healthy state and could be discharged finally (overall survival 60%). Survival was superior in those patients with normal renal function (10/13 (77%)) as compared to patients with ARF (2/7 (29%)). The surviving patients needed additional respirator treatment for 7–53 days (mean 22 days). During pECLA therapy none of the patients suffered from spontaneous bleeding forcing the interruption of treatment. No signs of arterial malperfusion in the punctured legs were noted. In one case a localized bleeding at the arterial puncture site required surgical intervention.

Technical problems included thrombosis of the (venous) inflow cannula (*n* = 5) resulting in a decreased *F*<sub>MO</sub>. The cannulas then were replaced in Seldinger's technique. Four MOs had to be exchanged due to thrombus formation (*n* = 2) or plasma leakage (*n* = 2). In one case the MO was contaminated with *Candida albicans* which was detected macroscopically close to the gas outlet orifice. After the MO's exchange microbiological examination of the outer membrane layer confirmed the diagnosis. Nevertheless, *Candida* did not penetrate the gas-blood barrier as shown by electron microscopy. Moreover, there was no evidence for the patients infection with *Candida* (negative

blood culture and antibody status). Three MOs were in continuous use for 22, 27, and 32 days, respectively. None of the technical complications caused an interruption or termination of pECLA therapy.

#### 4. Discussion

Several animal studies on pECLA [10–13] and pumpless extracorporeal CO<sub>2</sub> removal [14–16] have been published in the late 1980's and early 1990's. So far, the pumpless method has never been applied to humans. This is the first clinical report on pECLA applied to patients suffering from severe forms of ARDS.

As in the pump-driven technology, the method is based on the premise that 'lung rest' facilitates alveolar repair and helps to avoid baro- or volutrauma of high pressure ventilation. The evolution in membrane and oxygenator technology provides us with low-resistance membrane gas exchangers that allow a significant flow even when the circuit is not driven by a pump. In our setting, the mean extracorporeal flow was 2.6 l/min which represented approximately 25% of the patients mean cardiac output. In our individual experiences the extracorporeal flow exceeded 4 l/min, which reaches the range of pump-driven systems. By establishing appropriate hemodynamic inclusion criteria a rather hyperdynamic group of patients was selected. The driving pressure gradient between MAP and CVP occasionally was enhanced by norepinephrine infusion. It was our experience that immediately after pECLA onset simultaneous with the better oxygenation the catecholamine supply could be reduced or even withdrawn in most patients. Although the system does not provide active assistance to patients suffering from cardiac failure (and, therefore, is contraindicated in such patients) it may be helpful to a certain extent in patients with mild degrees of cardiac dysfunction and catecholamine resistance.

The blood gas exchange capacity of pECLA was generally found to be sufficient. The key effect of both ECLA techniques, pump-driven or pumpless, is a nearly 100% oxygen saturation of the blood gas passing the oxygenator. Thus, the flow through the MO is one of the critical parameters for the whole body oxygenation. As with pump-driven ECLA maximum flow rates of 4 to 6 l/min can be achieved, physically pECLA per se will never be equal effective. Therefore, pECLA should be considered only as a supportive therapy but could not totally replace ventilator therapy.

The incidence of both technical and patient-related complications of ECLA is much more common in adults than in neonates [4,17]. Gille et al. reported on 11 technical complications in 65 patients including three deaths [18]. In pump-driven ECLA the most common technical complication is oxygenator failure (19%) followed by cannula problems (12%), tubing rupture (5%), pump malfunction (3%), and heat exchanger malfunction (1%) [4]. The

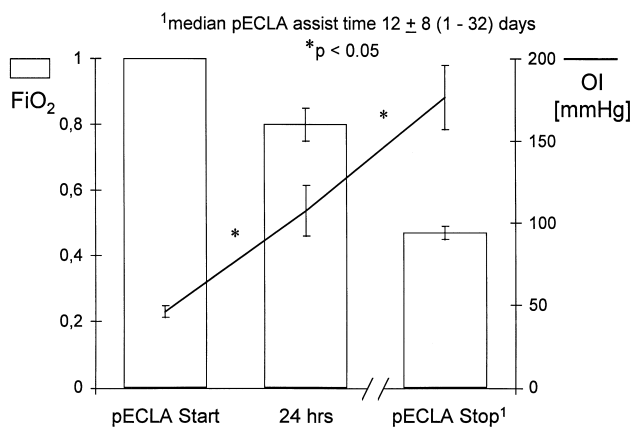


Fig. 2. Effectiveness of pumpless extracorporeal lung assist (pECLA) with respect to oxygenation index. OI, paO<sub>2</sub>/FiO<sub>2</sub>.

absence of fatal technical complications was one of the important findings of this study. Since our system worked without pump and heat exchanger technical problems were restricted to oxygenator failure (20%) and cannula problems (25%). Thrombus formation within the oxygenator is one of the commonest problems in extracorporeal oxygenation. This phenomenon is well known amongst perfusionists in the setting of cardiopulmonary bypass [19]. Research hypothesizes that it is the activation of platelets that subsequently may cause fibrin deposition. However, the primary etiology of this phenomenon remains unknown. The relatively high incidence of thrombus formation within the MO or the venous cannula may be due to the low heparin dosage which was chosen by us. On the other hand, we did not observe any bleeding complication nor clinically evident embolisms due to systemic coagulation defects. This is a clear advantage over pump-driven ECLA, which entails a significant risk of hemorrhagic complications (17%) and bleeding at the surgical site (28%) [4].

Another advantage of the system were the easy handling properties. By omitting the pump the total length of the AV-shunt could be kept at a minimum, thus facilitating nursing care and other supportive therapies such as ventilation in prone position or kinetic therapy. Inter-department patient transports can easily be performed without interruption of pECLA therapy.

Patient outcome observed in our study was superior to mortality rates from the European ECLA centers published in the mid-nineties (49%) [6]. The Extracorporeal Life Support Organization (ELSO) registry report of 1997 revealed a 51% mortality of adult pump-driven ECLA when used for pulmonary support [7]. ECLA for cardiac support reported to ELSO provided a survival rate of only 42%. The overall survival in our study group was 60%. As we focused on hypoxemia and preserved hemodynamics when selecting our study group, renal failure at the time of entry was no exclusion criterion. Thus, our study population was heterogenous with respect to that parameter. Although initially all patients benefited from improved oxygenation, the final outcome was dramatically worse in the ARF patients (71% mortality) compared to non-ARF patients (23% mortality). Therefore, renal failure appears to be an unfavourable prognostic factor for pECLA therapy. When renal dysfunction is considered part of multiple end-organ dysfunction in the complex of arterial hypoxemia, it seems to be favourable to shift pECLA indication towards earlier stages of the disease.

Besides the encouraging early clinical results pECLA should also contribute to cost effectiveness in the management of acute lung failure. Oxygenator longevity, no additional costs for pump-heads, pumps and warming devices, decreased costs of complication management and less need for transfusions will further decrease therapy costs as compared to conventional ECLA therapy.

In conclusion, pECLA seems to be a useful supportive therapy in selected patients with severe ARDS and oxygenation

failure but preserved hemodynamics. For current practice, ease of availability and handling, high effectiveness, low complication rate and relatively low costs made the method preferable to pump driven ECLA.

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## Appendix A. Conference discussion

**Mr A. Sosnowski (Leicester, UK):** You can achieve very limited support with both v-oxygenation and CO<sub>2</sub> removal; my guess this is similar to IVOX. Have you tried IVOX? You can't compare it to ECMO. None of my ECMO patients would survive with such a support.

**Dr Liebold:** I agree there are a number of other supportive therapies, and IVOX is one of them. But we felt very comfortable with this system because it's very simple and I think we could demonstrate that we have a very low number of complications.

**Mr Sosnowski:** You didn't indicate how long patients had been on ventilator before.

**Dr Liebold:** Ten days. A mean of 10 days.

**Mr Sosnowski:** On high pressure?

**Dr Liebold:** Yes. High pressure ventilation, surfactant replacement therapy, high-frequency jet ventilation, all kind of supportive therapy you can imagine. And there was a consensus that otherwise all patients would have died.

**Dr S. Svenmarker (Umea, Sweden):** You mentioned that the flow through your circuit was about 2.6 l. I'm interested to know how much oxygen are you able to transfer through this unit. What I would assume is

that the oxygen saturation before the oxygenator is rather high and also the oxygen transfer might be limited by this.

**Dr Liebold:** Because of the limited time I was not able to present all the parameters measured. The mean oxygen saturation in the arterial blood before the oxygenator at the time of pumpless ECLA start was 84.3%, and the oxygen saturation of blood passing the oxygenator was 99.9%. In other words, all the blood passing the oxygenator will be almost 100% oxygen saturated. Thus, the trans-MO flow and not the oxygen saturation seems to play the key role in the whole body oxygenation. As with our system flow rates of 25% of the patients cardiac output were reached and the flow even exceeded 4 l/min in individual cases we came in the range of conventional pump-driven systems.

**Dr V. Kucera (Prague, Czech Republic):** Your device is dependent on the arteriovenous pressure difference. What was the smallest patient you could use?

And second question is, is the device commercially available and who is producing this oxygenator?

**Dr Liebold:** The smallest patient we used was an adult. We had only adults. The youngest was a 17-year-old boy with a Waterhouse–Fridrichsen syndrome. He had a height of about 170 cm. So up to now we didn't apply the method to children. And to your second question, the components are commercially available, of course. You can buy the oxygenator, you can buy the silicone rubber tubings and all those things, but the system, the idea, is a new one.

**Dr Kucera:** You mentioned the low resistance of the oxygenator, but what was the company you used?

**Dr Liebold:** The company is Jostra (Hirtlingen, Germany). We measured the resistance in a particular patient with a cardiac output of about 10 min and the mean arterial pressure of 90 units.