The Addition of a Membrane Oxygenator to a Ventricular Assist Device in a Patient with Acute Respiratory Distress Syndrome

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Abstract: A 12-year-old boy with Marfan’s syndrome required a biventricular assist device (VAD) after an aortic root replacement. The patient developed acute respiratory distress syndrome and required escalating ventilator support. We hypothesized that the addition of a membrane oxygenator in series with the assist device would improve gas exchange and allow for a more lung-protective ventilator approach. A membrane oxygenator was placed in series with the right VAD resulting in a blood path of right atrium to VAD to oxygenator to pulmonary artery. Circuit function was gauged by monitoring flow and oxygenator pressures and periodic circuit inspections and oxygenator blood gases. Heparin was titrated to maintain unfractionated antifactor Xa levels of 3–7 IU/mL and partial thromboplastin time of 60–80 seconds. The initial sweep gas supplying the oxygenator was 5 L/min at an FIO2 of 1.0, which achieved a pH >7.40 and a PF ratio >250. The pre- and post-oxygenator pressures were 55–60 mmHg and 45–50 mmHg, respectively, and the measured flow at the oxygenator outlet was 2.0–2.2 L/min. The patient was changed from high-frequency oscillatory ventilation to pressure-controlled synchronized intermittent ventilation with pH maintained at 7.35–7.40 and PF ratio >250. Paralytics were discontinued and the patient’s neurologic condition was deemed intact. The patient hemorrhaged after a sternal closure and required transfusions and antifibrinolytics that led to thrombus in the membrane and membrane circuitry, which were replaced without incident. The patient’s respiratory status remained stable; however, his overall condition worsened as a result of additional organ dysfunction and septicemia, and he did not survive. The addition of a membrane oxygenator to a VAD is feasible and supplements gas exchange permitting the use of more lung protective ventilation.

Keywords: cardiac surgery, congenital heart disease, ECMO (extracorporeal membrane oxygenation), circulatory assist devices, ARDS (acute respiratory distress syndrome).

OVERVIEW

A 12-year-old boy with Marfan’s syndrome and evolving aortic root dilation received a valve-sparing ascending aortic root replacement. The surgical course was notable for significant bleeding, compromised coronary blood flow, and a total bypass time of 705 minutes including 298 minutes of crossclamp time. Attempts at weaning from cardiopulmonary bypass (CPB) were unsuccessful as a result of biventricular failure, and the patient was transitioned to extracorporeal membrane oxygenation (ECMO).

After stabilization, the patient underwent cardiac catheterization, which confirmed a good anatomical repair and the presence of severe biventricular failure. During the subsequent ECMO course, the patient received Rh-positive blood as a result of a statewide shortage of O-negative blood, and bedside head computed tomography scan was normal at ECMO hours 18 and 34. Anticipating the need for prolonged cardiac support and the presence of a favorable neurologic examination, the patient was deemed a candidate for a biventricular assist device (VAD) as a bridge to recovery at ECMO hour 58. Continuing ECMO as a bridge to recovery was considered riskier because the recovery period was uncertain, and a lengthy ECMO course may have been associated with further complications.

The AB5000™ Circulatory Support System (Abiomed Inc., Danvers, MA) was prepared, bi-VAD was implanted, and the two assist devices were connected to left and right heart inlet and outlet cannulae, left ventricular to aorta and right atrium to pulmonary artery, respectively. Assist device flow rates were quantified at 4–5 L/min at a rate of 40–50 beats/min, and the patient was weaned off CPB but required high mean airway pressures (mPaw) to achieve an SpO2 > 85%. In the postoperative period, the VAD maintained adequate blood pressure and perfusion but the patient developed findings consistent with acute respiratory
distress syndrome (ARDS), including bilateral lung infiltrates and a PF ratio <200.

Over the next 72 hours, the patient’s lung compliance worsened and he required high-frequency oscillatory ventilation (HFOV) to achieve a pH >7.32 with a corresponding PF ratio of 53–112. HFOV settings were mPaw 36–40 cm H$_2$O, FIO$_2$ .70–1.0, P-amp 70–80 cm H$_2$O, and a frequency of 5 Hz. Additionally, the patient developed renal dysfunction and required continuous renal replacement therapy (CRRT).

Although the patient remained somewhat clinically stable, his sternum remained open, lung function was not improving, and HFOV settings were considered maximized. We hypothesized that the addition of a membrane oxygenator in series with the VAD would improve arterial blood gases so that a more lung-protective ventilator strategy could be applied.

**DESCRIPTION**

A Quadrox-iD adult diffusion membrane oxygenator (Maquet Cardiopulmonary, Hirrlingen, Germany) was placed in series with the right-sided VAD. The membrane was configured with 3/8-inch tubing for the membrane inlet and outlet lines connected to an otherwise half-inch circuit. A bridge around the membrane was restricted with an adjustable clamp (Figure 1). The blood path was therefore right atrium-to-VAD-to-membrane-to-pulmonary artery. The actual connection took approximately 2 minutes and the left-sided VAD was left-ejecting.

Circuit function was gauged by monitoring flow (Transonic HT110; Transonic System, Inc., Ithica, NY) and pressures (DLP 63000/64000; Medtronic Inc., Minneapolis, MN), circuit inspections every 4 hours and periodic pre- and post-membrane blood gases. Heparin was titrated to maintain unfractionated antifactor Xa levels of .3–.7 IU/mL and partial thromboplastin time 60–80 seconds.

This intervention was approved by the Children’s Hospital Boston Institutional Review Board. The off-label use of this membrane oxygenator beyond its approved maximum duration of 6 hours was acknowledged.

The initial sweep gas supplying the oxygenator was 5 L/min at an F$_1$O$_2$ of 1.0, which achieved a pH >7.40 and a PF ratio >250. The pre- and post-oxygenator pressures were 55–60 mmHg and 45–50 mmHg, respectively, and the measured flow at the oxygenator outlet was 2.0–2.2 L/min. The patient was subsequently converted from HFOV to conventional mechanical ventilation in the pressure-controlled synchronized intermittent ventilation mode. Ventilator settings, titrated to achieve a pH of 7.35–7.40, were peak inspiratory pressure/positive end-expiratory pressure 32–35/12–15 cm H$_2$O with resultant tidal volumes of 6–8 mL/kg, rate 12/min, and mPaw 16–18 cm H$_2$O. The F$_1$O$_2$ was decreased from 1.0–.5 with a PF ratio maintained >250.

Over the next 48-hour period, the sweep gas was titrated to 2 L/min at an F$_1$O$_2$ of .50 with pH maintained at 7.35–7.40 and PF ratio >276. Paralytics were discontinued and the patient’s neurologic function was deemed intact. Oxygenator pressures and flow rates were essentially unchanged and periodic pre- and post-oxygenator blood gases obtained from the circuit demonstrated adequate CO$_2$ clearance and oxygenation.

Two days later, the patient developed significant bleeding after sternal closure and required multiple transfusions and antifibrinolytics. This led to thrombi in the membrane and circuit connections that were replaced without incident. Over the next 2 days, the patient’s respiratory status remained stable; however, CRRT was still required, hepatic dysfunction persisted, and hypotension associated with septicemia developed requiring increased vasopressor therapy. Twenty-four hours later, the patient’s condition greatly worsened, care was redirected, and the patient subsequently died.

**DISCUSSION**

We spliced a membrane oxygenator in series with a VAD for a patient requiring biventricular support and with

![Figure 1. Schematic of the ventricular assist device with an added membrane oxygenator.](image-url)
severe ARDS. Our premise that gas exchange could be improved thus permitting the use of a more lung-protective ventilator approach was confirmed. The change from HFOV to conventional mechanical ventilation allowed paralytic discontinuation, better monitoring of lung compliance, and use of more lung-protective ventilator settings.

Before clinical use, we completed a circuit mock-up to ensure that circuit-to-VAD connections were suitable and could be executed efficiently. We determined that half-inch tubing was needed to make the VAD connections which required a $1/2'' \times 1/2'' \times 3/8''$ adapter with the 3/8-inch ports matching the 3/8-inch openings of the membrane. The half-inch bridge around the membrane and primarily half-inch circuit were used so that VAD flow could be maintained during potential membrane replacement with minimal resistance to right VAD output.

Limitations of our system were the unavailability of a half-inch flow sensor and the imprecision of the bridge clamping mechanism. Flow was measured with a 3/8-inch sensor at the membrane outlet, which did not reflect the flow traversing the bridge. The difference in the measured flow with the bridge partially clamped and completely occluded could provide an estimate of the flow through the bridge. Our main objective was the preservation of some flow through the bridge to avoid stagnation and clot formation.

One modification to consider is a pre-primed and isolated bridge that could be accessed only if needed. This is common in conventional ECMO circuits in which stopcocks are opened and low flow rates used to maintain circuit patency while a patient is isolated from support for assessing cannulation readiness or troubleshooting circuit issues. If a similar bridge system were used, the output of the right VAD may dramatically change in the presence of the high resistance through the stopcocks. Alternatively, eliminating the bridge would be a possibility because these membranes are easily prepared and could be replaced with as brief an interruption in VAD support as was the initial connection.

A similar application of a membrane oxygenator inserted into a VAD circuit has been reported by Garcia-Guereta (1). In their case report, a Quadrox membrane was used with an Excor left VAD position and no bridge was positioned around the membrane.

Possible alternatives for supplementing gas exchange in this patient may have included resumption of ECMO and pumpless arteriovenous CO$_2$ removal (2), both of which would have required additional vascular access.

Reinstituting ECMO may have sufficiently supplemented gas exchange and may have been accomplished by cannulation of the right internal jugular vein with a double-lumen venous-venous cannula (3), but it is unclear how a gravity-dependent ECMO system with a roller pump would have interacted with the pumping mechanisms of the VAD. This also would have required additional resources, more blood product exposure, and added risk.

Initiating pumpless arteriovenous CO$_2$ removal may have been a somewhat simplified approach to conventional ECMO but would have required femoral arterial and venous access (4). The passive blood flow of this configuration is through an extrapulmonary arterial–venous shunt and is dependent on a fairly robust cardiac output. One example of such a system is interventional lung assist or iLA (Novalung, Talheim, Germany) (5).

The introduction of polymethyl pentene oxygenators has been a significant advancement in long-term extracorporeal life support (6). Principle attributes include less susceptibility to plasma leak, low priming volume, low resistance, and ease of preparation (7). Incorporating a traditional silicone or microporous hollow fiber oxygenator in tandem with a VAD may not have been as feasible because of high resistance and potential plasma leaking, respectively.

It has been suggested that a paradigm shift toward streamlined extracorporeal life support systems is likely with a focus on smaller priming volumes, less foreign surfaces, and reduction in blood product use (8). Perhaps this shift will include long-term circulatory support devices that can easily be adapted to accommodate extracorporeal gas exchange for unanticipated respiratory failure. Until such systems are refined, the addition of a low-resistance diffusion membrane oxygenator to a VAD is feasible and improves gas exchange.

REFERENCES