Intravascular Membrane Oxygenation and Carbon Dioxide Removal –
A New Application for Permissive Hypercapnia?

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Introduction

The adult respiratory distress syndrome (ARDS) was first described by Ashbaugh and Petty in 1967 in 12 adult patients with the clinical features of dyspnea, hypoxemia, decreased pulmonary compliance, and diffuse pulmonary infiltrates (1). Diagnostic criteria of ARDS are slightly different in one clinical series to another, but generally have the following characteristics: 1) predisposing event resulting in respiratory failure, 2) non-cardiogenic pulmonary edema, 3) clinical signs of respiratory failure, 4) diffuse pulmonary infiltrates, 5) arterial partial pressure of oxygen \( \text{paO}_2 < 50 \text{ mm Hg} \) with fractional inspired concentration of oxygen of 0.6, and variable amounts of positive end-expiratory pressure (PEEP) (14, 17). It appears that ARDS represents a final common pathway to a variety of noxious stimuli or injuries to the lung. Currently, there is no direct treatment for ARDS, so the primary goal for treating ARDS is appropriate respiratory support with maintenance of adequate oxygenation while attempting to minimize oxygen toxicity and barotrauma.

Mortality from severe ARDS was approximately 90% in both the control and treatment arms in the United States National Institutes of Health extracorporeal membrane oxygenation (ECMO) trial of the 1970s (17). Although critical care techniques, antibiotics, invasive monitoring, etc., have improved over the last 20 years, the mortality from severe ARDS remains unchanged. In a prospective evaluation of patients with ARDS, Cox and Zwischenberger recently documented an institutional mortality of 81% for patients with severe ARDS (2). Patients in that study had a \( \text{paO}_2 < 60 \text{ mm Hg} \) after 24 h of \( \text{FI02} \) of greater than 50% and positive end-expiratory pressure of 10 cm H\(_2\)O. Alternate entry criteria were \( \text{paCO}_2 > 40 \text{ mm Hg} \) with a minute ventilation of 150 ml/kg/min. Clearly, ARDS mortality remains high despite advances in critical care. Recently, Hickling et al. described decreased mortality in patients with ARDS with deliberate hypoventilation with low tidal volumes/low inspiratory pressures to minimize barotrauma while allowing \( \text{paCO}_2 \) to rise (permissive hypercapnia) (6). However, substantial reductions in peak airway pressures may

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be limited by the development of acidemia as CO$_2$ rises beyond the capacity of the kidney to compensate for the acid load. Intravascular oxygenation/carbon dioxide removal (IVOX) adds oxygen to and removes carbon dioxide from the venous blood to allow a reduction in ventilator support. We have hypothesized that permissive hypercapnia coupled with IVOX to augment CO$_2$ removal may permit significant reductions in peak airway pressures/barotrauma. We present the history of the development of IVOX, in vivo animal data/experience, and initial clinical experiences/future directions of IVOX in managing patients with respiratory failure.

**Specifications/performance**

The intravascular oxygenator, or IVOX, is a small, elongated, hollow-fiber membrane oxygenator which lies in the vena cavae. The hollow fibers are connected to a dual-lumen (approximately 10-French (F) diameter) gas conduit which exits the skin. The hollow fibers are joined together in a potted manifold which communicates with the dual-lumen gas conduit at both is proximal and distal ends (Fig. 1). A vacuum pump draws oxygen into the multiple hollow-fibers from an oxygen source via the gas inlet. The exit gas is analyzed for carbon dioxide (Fig. 2).

The critical design developments by Mortensen et al. (8, 9) allowed the IVOX to progress from a theoretical to a clinical device. There is no extracorporeal circula-

![Fig. 1. A photograph of the IVOX. The double lumen gas conduit attaches to the multiple hollow fibers at the proximal and distal manifolds. Inlet gas (oxygen) flows to the distal manifold and flows through each individual hollow-fiber. The exit gas is rich in carbon dioxide and flows out the exit limb.](image)