Volotrauma and the Intravenous Oxygenator in Patients with Adult Respiratory Distress Syndrome

The Problem

Evidence has been accumulating inexorably that mechanical ventilation of patients with adult respiratory distress syndrome (ARDS) causes further lung injury. Laboratory and clinical research indicates that such mechanical injury is actually "volotrauma": overdistention, stretching, and ripping of the residual lung.

During ARDS, lung volume first is reduced by the primary injury, usually sepsis, trauma, or pneumonia, increasing vascular permeability, filling the lung with plasma and cells, and consolidating and increasing lung weight by 1 or 2 kg. Usually at about this point, the intensive care physician will intubate the patient's trachea and begin some mode of partial or total mechanical ventilation, hoping to recruit and distend collapsed alveoli and assure their ventilation. Too often, this solution exacerbates the problem, by producing volotrauma.

Experiments have shown that even a normal lung will become overdistended when subjected to a large tidal volume and that rapid interstitial and alveolar edema and ruptured capillaries result.1-5 Interestingly, if we first strap a normal animal's chest to restrict its expansion and then ventilate the lungs at normal (10-15 ml/kg) tidal volumes but, because of the strapping, very high inspiratory pressures occur, we do not produce lung injury.6 Volotrauma and not barotrauma, then, is causing additional injury to the already acutely injured lung.

The Solution

A number of strategies, some simple and some complex, can be used to reduce lung destruction by volotrauma. Simple ventilatory strategies include: maneuvers aimed at reducing the tidal volume, such as intermittent mandatory ventilation (IMV) at low tidal volumes and pressure controlled ventilation (PCV) with inspiratory pressures restricted to 30 cmH2O. An extension of this strategy is to more markedly reduce the tidal volume, accept a reduced minute ventilation and allow the PaCO2 to rise.7 This mode of ventilation is called "permissive hypercapnia" and is now a common therapy in Europe, where it is usual for physicians to allow PaCO2 values to reach 90 mmHg. Unfortunately, while it reduces volotrauma, there is no evidence that permissive hypercapnia increases survival in ARDS.

Some complex future solutions include extracorporeal CO2 removal (ECCO2R) and the intravenous oxygenator (IVOX). If we hypothesize that overdistention of the residual healthy lung is the crux of the problem, then by performing gas exchange via an artificial lung, exchanging gases such as a fish does with its gill, we should be able to circumvent the volotrauma problem. Indeed, during the period of extracorporeal support, physicians have statically distended or even allowed the ARDS lung to completely fill with edema fluid and perform no gas exchange, nonetheless, the lung at times has proved capable of healing.8-10 The analogy to the use of extracorporeal hemodialysis for a month or two to perform fluid and electrolyte exchange for patients in acute renal failure is obvious.

This dream is an old one, but making and proving it a reality has remained elusive. A multicenter randomized trial in 1977 showed that short-term venoarterial bypass (mean perfusion period, 5 days) with artificial lungs was ineffective in ARDS, primarily because bacterial and viral pneumonia, the underlying cause of ARDS, could not be reversed.11 It is true that, since that study was performed, short-term venoarterial bypass for full-term newborns with persistent pulmonary hypertension and meconium aspiration, pioneered by Bartlett and coworkers,12 has proved quite successful. But persistent pulmonary hypertension and ARDS are quite different syndromes, and while I do not have the space to discuss them here, suffice it to say that the means for treating one may not provide the means for treating the other.

In the past 15 years, a few centers, primarily in Europe, have persisted with venovenous long-term perfusion in ARDS (which they termed ECCO2R).13 This bypass technique is capable of total extracorporeal support of O2 and CO2 exchange. While the arterial PO2 may not be very great, ECCO2R requires large extracorporeal blood flow rates (2-4 L/min) and systemic heparinization. The risks of this technique are thrombocytopenia, hemorrhage, and mechanical failures. Despite these significant risks and a major personnel requirement for skilled perfusionists, adult ECCO2R is commonly employed for perfusions lasting 3-8 weeks in Milan, Marburg, and Berlin. The survival rate in several hundred ARDS patients treated with ECCO2R is near 50%.8 We must bear in mind that the selection criteria are not standardized; many etiologies,

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including posttraumatic ARDS, are treated; the patients are often young; and there is no control group of conventionally managed patients. Further, the appeal of this technique is diminished by knowledge gained in recent years that only infrequently is hypoxemia the cause of death of patients with ARDS (20–35%); most often ARDS is only one expression of multiorgan failure in the sepsis syndrome. It is unlikely that a therapeutic strategy in ARDS based solely upon supporting the function of a single organ will be successful.

Now the IVOX enters upon the scene with a fresh and appealing approach. A small, rather uncomplicated intracorporeal prosthetic lung, the IVOX should require fewer personnel and a simple cannulation and perhaps be amenable to heparin bonding and the reduction of anticoagulation levels. The report in this issue of ANESTHESIOLOGY by High et al. is a description of their pioneering results with IVOX therapy in five patients with ARDS. Their initial data may not seem impressive: the maximal O₂ and CO₂ exchange via this intracaval device was only about 20% of basal production, and we expect that reducing minute ventilation by 20% will not provide the lung much protection from volutrauma. The fact is, however, that the IVOX approach holds promise, and we must analyze its present limitations in order to design and test a more advanced device with greater capacity to transport respiratory gases.

It is likely that, given the laws governing respiratory gas transport, the IVOX must contain at least twice as many capillaries as are now contained in the largest IVOX, and that it may be necessary to relocate the device into the mixed venous stream, where there is greater venous blood flow than in the cava. The 0.5-m² capillary surface designed into the large IVOX theoretically should provide 70–130 ml/min of gas transport, and this rate was achieved. Analysis of O₂ or CO₂ transport per square meter of prosthesis surface area shows that 140–260 ml/m²·min⁻¹ of both gases was transferred between the blood and gas phases. In comparison, the natural adult lung has 75 m² of capillary surface area, constructed of course for maximal exercise, and a maximal oxygen transport rate (VO₂) of 3.3 L/min or 44 ml O₂/m²·min⁻¹. The IVOX then, while achieving an impressive gas transport efficiency per square meter, is underpowered if we are aiming for total basal human respiratory support, requiring near 260 ml O₂/min.

An inherent problem in using the inferior vena caval position for intravascular oxygenation results from the fact that sepsis, the most common cause of ARDS, is characterized by a high cardiac output and an elevated mixed venous P O₂. This puts the IVOX at a severe disadvantage since in sepsis less O₂ can be added to the venous blood. Another possible handicap to this IVOX position is that it may obstruct the cava, raising caval pressure and increasing venous congestion of splanchnic organs such as the liver or kidney. Adding a square meter of polypropylene capillary surface to the bloodstream could add another problem, providing intravascular caves and crannies in which bacteria can hide, and presenting a formidable challenge to eradicating bloodstream infection.

These problems for the IVOX should not be considered insuperable; little effort has yet been made to solve them. Several pathways for exploration are clear:

1. Perform gas exchange on the entire venous stream. The IVOX could be tested as a right atrial oxygenator, right ventricular oxygenator or, even better, a pulmonary artery oxygenator. Perhaps, as Snider et al. have already proposed this could be done by modifying a pulmonary artery catheter device, although other geometries and conceptions must be developed.

2. Increase gas exchange efficiency to reduce the size and surface area of the prosthesis. We have emerged from the era of the blood-gas sandwich and the sheath oxygenator, designs that I consider the horse-and-carriage oxygenator days in which gas exchange rates reached 25–60 ml O₂/m²·min⁻¹, and have arrived at the current status attaining rates of 140–260 ml/m²·min⁻¹. In the future, an intravascular oxygenator may be constructed, possibly employing secondary flows to augment stirring, disrupting the boundary layer that impedes oxygen transport. Designing, constructing, and testing such a device will take creativity, skill, and precision engineering. Once such a device is tested and proved reliable, improved biocompatible materials, perhaps with anticoagulant and antiseptic properties can be produced to reduce the hazards of anticoagulation and infection.

Almost all past advances in oxygenator materials and design have been driven by the considerable market for short-term cardiopulmonary bypass techniques. With this simple, less expensive alternative to extracorporeal membrane oxygenation, perhaps artificial organ manufacturers will respond to the promise of this technology to improve long-term gas exchange assistance of adults and children with severe respiratory failure.

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