An alternative approach to enhanced gas transfer in an intravascular respiratory support catheter

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***Abstract* – A potential therapy for respiratory failure involves the use of an intravascular respiratory support catheter. High gas exchange efficiency is necessary in the design of such a catheter to meet metabolic oxygenation and carbon dioxide removal requirements due to surface area limitations of the device. Active mixing techniques such as balloon pulsation have been implemented in the past to augment this efficiency. This paper evaluates an impeller as an alternate mixing technique to increase the gas exchange per unit surface area of an intravascular respiratory support catheter. The level of gas exchange using the impeller technology was compared to currently used balloon technology. The O_2 transfer efficiency of the impeller device was 180 ml/min/m^2 compared to 70 ml/min/m^2 with the balloon device, and the CO_2 transfer efficiency of the impeller was 395 ml/min/m^2 compared to 138 ml/min/m^2 with the balloon device when tested in a mock vena cava flow loop using water. The higher exchange efficiency of the impeller suggests possible feasibility of this active mixing technology for use in intravascular artificial lungs.**

***Keywords* – impeller, balloon, oxygenation, CO_2 removal, artificial lung**

INTRODUCTION

An intravascular respiratory support catheter may be an alternative respiratory therapy to the currently used extracorporeal circuit for oxygenating blood and removing carbon dioxide. The intravascular device is inserted into the inferior vena cava, thus eliminating the priming volume and pump requirements typical of the extracorporeal circuit. The main advantages of the intravascular device include less personnel requirements, less equipment, and hence lower operating costs for the patient. Designing such a device is challenging because of the geometrical constraints imposed by the vena cava. The diameter and length of the vessel restrict the intravascular design to lower surface areas than typically used in extracorporeal membrane artificial lungs (about 0.2 m^2 vs. 2 m^2). To overcome surface area limitations, some intravascular devices have incorporated active mixing technology such as a pulsating balloon to increase the efficiency of the device [1]. The balloon draws in fluid across the fibers resulting in an increased local relative velocity between the fibers and fluid. These higher velocities reduce diffusional boundary layers on the liquid side and increase gas exchange. We hypothesized that by rotating an impeller within the fiber bundle, more fluid would be drawn across the fiber bundle, effectively increasing the local relative velocity between the fibers and the fluid [2]. This study investigates the impeller as an approach to increasing gas exchange within an intravascular respiratory support catheter and compares this method to use of a pulsating balloon.

METHODOLOGY

The intravascular respiratory support catheter was tested in an in vitro mock vena cava loop, as shown schematically in Figure 1. Water at 37°C and 3 liters per minute was pumped through a 1 inch tube in which the catheter was placed. Pure oxygen flowed at 5.5 liters per minute through the lumens of the fibers. The device consisted of a 0.17 m^2, 30 cm bundle of microporous hollow fiber membranes (Celgard Inc. Charlotte, North Carolina) wrapped concentrically around a coiled spring. The configuration allowed either a balloon or an impeller to be inserted into the center of the device, and also protected the fibers from rotation of the impeller. The impeller was made from a 4 by 8 by 300 mm long piece of aluminum that was heated and twisted 3 times. The latex balloon had a volume of 11 cm^3, and a length of 30 cm. The maximum achievable rotation rate with this configuration was 5500 rotations per minute (RPM) for the impeller, and the maximum balloon pulsation rate was 300 beats per minute (BPM) using helium as the shuttle gas. O_2 partial pressures at the inlet and outlet of the device were measured using a

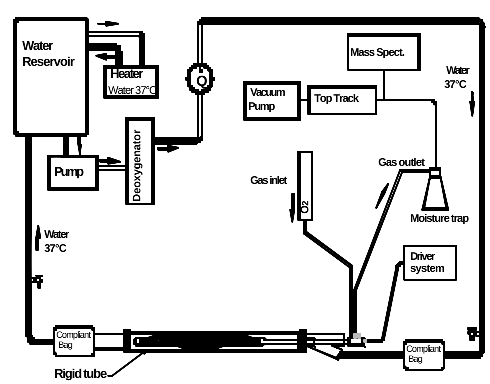

Fig. 1. In vitro bench circuit for evaluation of gas exchange performance of the respiratory support catheter using either an impeller or a balloon as the active mixing method. The test fluid in this experiment was water flowing at 3 LPM. Pure O_2 flowed through the fibers at 5.5 LPM.

blood-gas analyzer, (ABL-500 Radiometer Copenhagen, Denmark), and the O_2 transfer rates were calculated as the solubility of O_2 in water times the water flow rate and the difference in partial pressure between the inlet and outlet of the device. A mass spectrometer (MGA 1100, Marquette Medical Systems) was used to measure the concentration of CO_2, and a Fathom flow meter (GR-116-1-A-PV-02, Fathom Technologies) was used to measure the sweep gas flow rate. CO_2 transfer rate was calculated as the product of the sweep gas flow rate and percent CO_2 on the gas side and was normalized to an inlet PCO_2 of 50 mmHg [3].

RESULTS

Figures 2 and 3 show the results of the gas exchange tests for the impeller and balloon technology, respectively. The maximum O_2 transfer was 180 ml/min/m² with the impeller and 70 ml/min/m² with the balloon. The maximum CO_2 transfer with the impeller was 395 ml/min/m² and 138 ml/min/m² with the balloon device. In the absence of active mixing (zero impeller rotation and zero balloon pulsation) gas exchange in the devices was comparable. The difference in CO_2 gas exchange efficiency without active mixing was less than 2 ml/min/m², while the difference in O_2 efficiency was 16 ml/min/m².

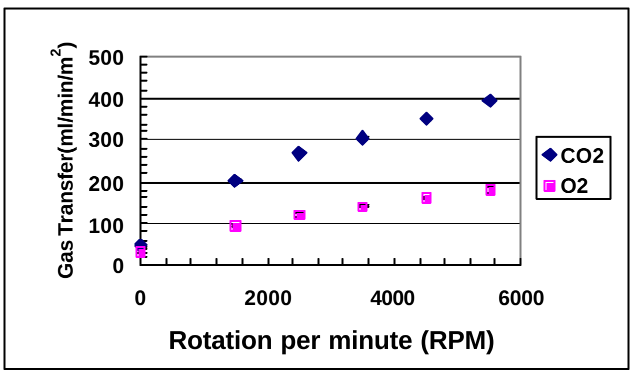

Fig. 2. O_2 and CO_2 transfer efficiencies versus impeller rotation rate for the intravascular respiratory support catheter.

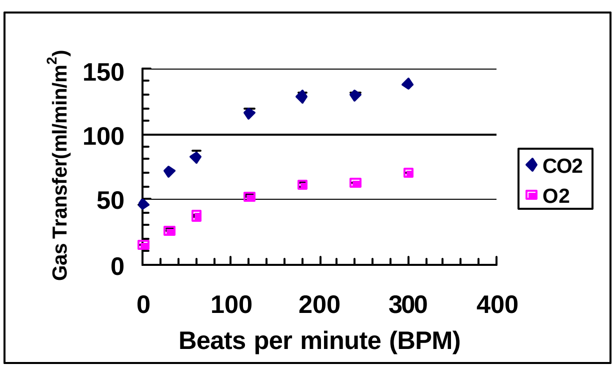

Fig. 3. O_2 and CO_2 transfer efficiencies versus balloon pulsation rate for the intravascular respiratory support catheter.

DISCUSSION

Active mixing using impellers and balloons can substantially increase gas exchange as shown in Figures 2 and 3. The impeller device at 5500 RPM, however, achieved 190% greater CO_2 transfer than did the balloon device at 300 BPM, while for O_2 the impeller device achieved 160% greater transfer. Thus the impeller appears more effective than the balloon in enhancing gas exchange in our respiratory support catheter. This is most likely attributed to the higher velocity of the liquid relative to the fibers that can be practically created by the rotation of an impeller compared to the pulsation of a balloon.

An estimate of the generated liquid-side velocities, V, can be performed for the balloon and impeller devices. For the balloon device V can be estimated by dividing the balloon stroke displacement (balloon radius) by half the oscillation period, yielding:

$$V_{balloon} \cong \frac{300\,beats}{\min} * 2 * 0.17\,cm \cong 100\frac{cm}{\min}$$

For the impeller device V can be estimated by multiplying the rotation rate by the radius of the impeller, yielding:

$$V_{impeller} \cong \frac{5500\,rotations}{\min} * \frac{2\pi\,rad}{rotation} * 0.4\,cm \cong 14000\frac{cm}{\min}$$

Thus characteristic fluid velocities in the fiber bundle may be 10-100 fold greater with impeller rotation compared to balloon pulsation.

Future studies will include gas exchange testing in blood and assessment of blood cell damage associated with impeller catheters compared to balloon catheters.

REFERENCES

[1] Hattler, B. G., Reeder, G. D., Sawzik, P. J., Lund, L. W., Walters, F. R. Shah, A. S., et al. Development of an intravenous membrane oxygenator: enhanced intravenous gas exchange through convective mixing of blood around hollow fiber membranes. Artif. Organs 18: 806-812, 1994.

[2] Makarewicz A. J., Mockros, L. F., Anderson, R. W., A pumping intravascular artificial lung with active mixing. ASAIO J. 39(3):M466-9, 1993.

[3] Golob J. F., Federspiel, W. J., Merrill, T. L., Frankowski, B. J., Litwak, K., Russian H., et al. Acute in-vivo testing of an intravascular respiratory support catheter. ASAIO J. 47(5) 432-437, 2001.

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