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Flow Visualization Study of a Pulsating Respiratory Assist Catheter

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Abstract

Our group is currently developing an intravenous respiratory assist device that uses a centrally located pulsatile balloon within a hollow fiber bundle to enhance gas exchange rate via active mixing mechanism. We tested the hypothesis that the nonsymmetric inflation and deflation of the balloon lead to both nonuniform balloon-generated secondary flow and nonuniform gas exchange rate in the fiber bundle. The respiratory catheter was placed in a 1-in. internal diameter rigid test section of an *in vitro* flow loop (3 L/min deionized water). Particle image velocimetry (PIV), which was used to map the velocity vector field in the lateral cross-section, showed that the balloon pulsation generated a nonuniform fluid flow surrounding the respiratory assist catheter. PIV was also used to characterize the fiber bundle movement, which was induced by the balloon pulsation. Gas permeability coefficient of the device was evaluated by using both the fluid velocity and the relative velocity between the fluid and the fiber bundle. The highest difference in the gas permeability coefficient predicted by using the relative velocity was about 17% to 23% (angular direction), which was more uniform than the 49% to 59% variation predicted by using the fluid velocity. The movement of the fiber bundle was responsible for reducing the variation in the fluid velocity passing through the bundle and for minimizing the nonuniformity of the gas permeability coefficient of the respiratory assist catheter.

Our group has been actively developing the intravenous respiratory assist catheter based on hollow fiber membrane technology to provide a temporary support for patients with acute or acute-on-chronic respiratory failure such as, acute respiratory distress syndrome (ARDS) and chronic obstructive pulmonary disease (COPD).^{1–3} The respiratory assist catheter consists of a constrained hollow fiber membrane bundle wrapped around a pulsating balloon. It is placed within the vena cava via the femoral vein insertion to supply oxygen and to remove carbon dioxide before the blood reaches the natural lung. As a result, the use of the respiratory assist catheter allows the lung to rest and heal, which is a benefit over mechanical ventilation. Respiratory support with this device may also potentially be less expensive and simpler than that with the extracorporeal membrane oxygenation (ECMO), because ECMO requires labor-intensive patient monitoring and increased blood or biomaterial contact in extracorporeal circuits.

Our previous study with an *ex vivo* flow loop⁴ and acute animal testing⁵ confirmed that a rapid pulsation of the centrally placed balloon was capable of enhancing the O₂ and CO₂ transfer rates greater than the nonpulsating device such as IVOX (intravenous oxygenator).⁶⁻⁹ The enhancement in gas exchange primarily results from the generation of convective blood flow perpendicular to the fiber¹ by the inflation and deflation of the balloon. Wickramasinghe *et al.*¹⁰ have looked at the oxygen exchange rate in hollow fiber membranes using both perpendicular and parallel flows to the hollow fiber membrane, and confirmed that at an equal value of flow per fiber surface area, the oxygen exchange permeability with cross flow was approximately 22 times higher than that with parallel flow. This substantial difference was mainly attributed to the dependency of liquid-side boundary layer thickness, which dictates the overall gas permeability of the respiratory assist device,¹ on the flow orientation. Cross flow generated a smaller diffusional boundary-layer thickness and, hence, a higher gas permeability coefficient than the parallel flow. Moreover, the uniformity of gas exchange enhancement at different regions of the respiratory assist catheter is strongly affected by the balloon-generated flow pattern, which depends on the geometry of the pulsating balloon. A balloon that collapses and inflates asymmetrically will generate nonuniform radial velocity surrounding the device, creating different enhancement of gas exchange at different regions of the fiber bundle. The current balloon incorporated in the respiratory assist catheter collapses into a flat, elongated shape and inflates into a circle as described in Figure 1. Eash *et al.*¹¹ have investigated the uniformity in the CO₂ exchange rate of the same respiratory assist catheter by selectively perfusing the sweep gas flow (helium) to different quarter regions of the fiber bundle for two different pulsation frequencies (120 and 400 beats/min). Even though the balloon collapsed nonsymmetrically, they found that the gas exchange rates at different quarter regions were uniform for the two pulsation frequencies, except the "back" quarter region, which was 16% to 20% higher than the other regions. They also observed visually that the balloon pulsation caused the movement of the fiber bundle that would affect the enhancement of the gas exchange rate by reducing the relative radial velocity between the fibers and the fluid. They concluded that the higher gas exchange at the back quarter region was attributed to less movement of the fiber bundle (higher relative velocity) at that region.

Different flow visualization techniques have been commonly used to investigate the flow pattern inside the medical device for design and operation improvements. One of the techniques is the particle image velocimetry (PIV) that measures the instantaneous velocity vector field within an illuminated plane of the fluid using light scattered by micron-sized tracing particles. Many investigators¹²⁻¹⁴ of ventricular assist devices and blood pumps have employed PIV technique to identify high shear stress and stagnation regions to minimize the occurrences of hemolysis and thrombosis. PIV technique is an ideal tool for measuring instantaneous velocity distribution in time-dependent flows, such as the flow surrounding the respiratory assist catheter at different times during balloon pulsation.

We hypothesized that the nonsymmetric pulsating balloon would lead to generation of nonuniform, balloon-generated radial flow and nonuniform gas permeability coefficient. PIV technique was used to map the velocity vector fields surrounding the respiratory assist catheter and characterize the motion of the fiber bundle outer surface. By using the velocity data, the variation in the gas permeability coefficient at different regions of the fiber bundle was evaluated and compared with the gas exchange data of Eash *et al.*¹¹ for the same respiratory assist catheter to answer the proposed hypothesis.

MATERIALS AND METHODS

Flow Loop and Respiratory Assist Catheter

The PIV experiments were undertaken in an *in vitro* flow loop as displayed in Figure 2. The flow loop consisted of a water reservoir, a centrifugal pump (LC-2CP-MD, March Mfg, Inc., Glenview, IL), a calibrated flowmeter (Gilmont Instruments Barrington, IL), a 1-in inner diameter (ID) rigid test section, Tygon tubing (Cole-Parmer, Vernon Hill, IL) and two compliance bags (0.5 L Neoprene Re-Breather Bag, Qosina, Edgewood, NY) located before and after the test section. The test section was made from acrylic plastic and had a square outer window for optical access. Tygon tubing was used to connect the test section and the reservoir, and deionized water was used in the present study. The balloon pulsation in the respiratory assist catheter was driven with a specifically designed pneumatic drive console consisting of vacuum and positive pressure reservoirs connected via alternating solenoid valves to a safety chamber enclosing an external balloon. The inside of this balloon was connected by a tube to the device balloon so that pressurization of the external balloon caused inflation of the device balloon and vice versa.

The respiratory assist catheter consists of 600 microporous hollow fiber membranes (x 30–240, Celgard Inc., Charlotte, NC), which were woven into fabric and wrapped around a 25-cm³ polyurethane balloon to create 10 layers of membrane. The length and diameter of the fiber bundle (with the fully inflated balloon) are 30 cm and 18 mm, respectively. The schematic of the respiratory assist catheter is displayed in Figure 2.

Particle Image Velocimetry Setup

The setup of the PIV is shown in Figure 3A. It consisted of a Nd:YAG laser system (Solo PIV III 15 Hz, New Wave Research Inc., Fremont, CA) emitting a 532-nm laser pulse; a Kodak CCD camera (Megaplug ES 1.0, Eastman Kodak Company, San Diego, CA); a cylindrical lens (Edmund Optics, Barrington, NJ); and a Pentium IV 1.6 GHz personal computer with a frame grabber (PIXCI D2X, EPIX Inc., Buffalo Grove, IL) and an eight analog output data acquisition card (NI-6713, National Instruments, Austin, TX). The Nd:YAG laser system has two laser heads (laser 1 and laser 2) that can be triggered independently. The cylindrical lens was used to generate a laser sheet with 2 mm thickness. The Kodak ES 1.0 camera is able to capture two sequential images within microseconds apart when it is operated under the triggered double exposure mode. The XCAP-standard v. 2.2 imaging software (EPIX Inc., Buffalo Grove, IL) installed on the personal computer was used to operate the Kodak camera. A close-up lens (60 mm f2.8D AF Micro- Nikkor, Nikon, Japan) was used with the Kodak camera to image the region of interest in the flow field.

Neutrally buoyant fluorescent polymer microspheres (35-6C, Duke Scientific, Palo Alto, CA) were used as the tracing particle to measure the flow field around the respiratory assist catheter. These particles emitted light with a longer wavelength (611 nm) via the Stoke shift mechanism when they were illuminated by a light with shorter wavelength (532 nm).

Operating Condition

The respiratory assist catheter was inserted into the test section and oriented so that the balloon collapsed in a horizontal direction. Two spacers were used to center the device inside the test section. The frequency of the balloon pulsation was fixed at 120 beats/min and the flow rate of the deionized water was set at 3 L/min. The Reynolds number of the flow, which was calculated based on the hydraulic diameter and the average fluid velocity, was 1650 for the flow with the fully inflated balloon. The present study focuses on one pulsation rate because the inflation and deflation times of the balloon are independent of the pulsation frequency. Therefore, the balloon-generated flow will be the same for different

pulsation frequencies as long as complete inflation and deflation of the balloon is maintained.

Particle Image Velocimetry Image Acquisition

Figure 3B displays the synchronization and timing schemes for the PIV measurements. A custom Labview 7.0 (National Instruments, Austin, TX) program was developed to generate three transistor-transistor logic (TTL) signals (signal 1, 2, and 3) for synchronizing both the laser and camera with the balloon pulsation of the respiratory assist catheter. Signal 1 is used to initiate the inflation or deflation of the pulsation. Signal 2 was sent at a specified time delay after signal 1 to fire the first laser pulse from the laser 1 and also to trigger the Kodak camera. The time delay of signal 2 defined the time at which the velocity fields surrounding the respiratory assist catheter were measured. It takes about 200 microseconds for the Nd:YAG laser to fire a 5-ns laser pulse after receiving the TTL trigger signal. Signal 3 was used to fire the second laser pulse from the laser 2. The first image was captured by the CCD camera after receiving signal 2 and showed the locations of the particles illuminated by the laser 1. The exposure period of the first image was set at 255 μ s. The second image had a fixed exposure period of 33 milliseconds (ms) and displayed the locations of the particles exposed by the laser 2. Therefore, a pair of images separated by a specific separation time was acquired by the camera at a specific time delay after the initiation of balloon inflation or deflation.

The PIV technique was used to measure the instantaneous velocity of the seeding particles in the radial plane. The digital camera was located at the end of the test section to capture images of the illuminated particles. An optical long pass glass filter (OG 550, Edmund Optic Inc., Barrington, NJ) was placed in front of the camera to eliminate the reflection of laser light on the fiber bundle surface. The imaging acquisition scheme of PIV was also used to characterize the movement of the fiber bundle at different time steps after the initiation of the inflation and deflation periods. Fiber bundle velocity was measured separately from that of the fluid velocity. The laser sheet was used to illuminate the surface of the fiber bundle and no fluorescent seeding particles were used in this measurement. To capture the image of the illuminated surface, the digital camera was located at the side and top of the test section to measure the velocity of the fiber bundle at four angular points located at 0°, 90°, 180°, and 270° relative to the horizontal plane. Four quarter annular regions consisting of those points are defined as the top, bottom, front, and back quarter regions (see Figure 1). The time separations between signals 2 and 3 for the velocity measurements of the fluid and the fiber bundle were 1 and 4 ms, respectively. Both the instantaneous velocities of the fluid and fiber surface were measured for an axial location of 20 cm from the proximal manifold (see Figure 2).

Analysis of Particle Image Velocimetry Images

For the fluid velocity measurement, the acquired two images were analyzed by using fuzzy logic enhanced PIV software (PIVPROC 6.53) developed by Wernet at the US NASA Glenn Research Center.¹⁵ The images were divided into 64 × 64 pixels interrogation areas with 50% overlapped interrogation areas. The same interrogation areas within each two images were cross-correlated to obtain the average displacement of particles. The camera scale factor was 31 μ m/pixel. The fuzzy logic method¹⁶ was employed to validate the correlation peaks in correlation processing to minimize the number of spurious velocity vectors. The average instantaneous velocity in each interrogation area was calculated by dividing the average displacement of the particles with time separation between TTL signal 2 and 3.

To measure the velocity of the fiber bundle outer surface, the pixel location of the illuminated fiber bundle surface was evaluated by using the XCAP-standard v.2.2 (EPIX

Inc.). The pixel displacement was calculated by subtracting the pixel location of the illuminated surface from the first image with that from the second image. The camera scale factor for this measurement was 24 $\mu\text{m}/\text{pixel}$. The instantaneous velocity was evaluated by dividing the average displacement of the illuminated surface with a known separation time.

Velocity and Gas Permeability Coefficient Calculations

Fifteen instantaneous pairs of images captured were used to calculate the ensemble-averaged velocity distribution of the fluid and the fiber bundle surface at different times after the initiation of the inflation and deflation periods. The ensemble-average velocity $U_i(r, \theta, t)$ was computed by using the following equation:

$$U_i(r, \theta, t) = \frac{\sum_{n=1}^N U_{i,n}(r, \theta, t)}{N} \quad (1)$$

where the subscripts i and n are for the component of velocity vector and the number of samples, respectively; r and θ indicate the radial and angular positions; N is for number of samples; and t is the specific time after the initiation of the inflation and deflation period. Standard deviation was calculated to describe the root mean square values of the velocity measurements. The time-averaged velocity, $\overline{U}_i(r, \theta)$ was evaluated by using the following equation:

$$\overline{U}_i(r, \theta) = \frac{1}{t_f - t_b} \int_{t_b}^{t_f} U_i(r, \theta, t) dt \quad (2)$$

where t_b and t_f indicate the time when the balloon starts inflating or deflating and the time when the balloon stops inflating or deflating. The trapezoid method was used to approximate the integration of velocity data in Equation 2. Both Equations 1 and 2 were also used to evaluate the magnitude of the ensemble and time-averaged relative velocity between the fluid and the outer surface of the fiber bundle.

The gas permeability coefficient, K_g , was estimated from mass transfer correlation obtained for flow through bundles of hollow fiber membrane. The convective mass transfer has the general form of $Sh = aRe^bSc^{1/3}$, where Sh is the Sherwood number; $Sh = K_g d / \alpha D$; Re is the Reynolds number, $Re = U_s d_h / \nu$; and Sc is the Schmidt number, $Sc = \nu / D$. This correlation involves the gas diffusivity, D ; the kinematics viscosity, ν ; the gas solubility, α ; the porosity of the fiber bundle, ϵ ; the hydraulic diameter of the fiber bed, d_h ; the diameter of individual fiber, d ; and the superficial velocity, U_s . Hewitt *et al.*¹⁶ and Federspiel *et al.*¹⁷ averaged appropriate cross-flow correlations from the literature over the relevant Reynolds number (about 0.6–15) and porosity (0.2–0.7) ranges for the balloon-generated flow in the respiratory assist device and obtained values of 0.524 and 0.523 for a and b , respectively. By dividing the value of $Sh(\theta)$ from two different θ locations, the ratio of $K_g(\theta)$ can be evaluated and depends on only the superficial velocity of fluid passing through the device at those two locations:

$$\frac{K_g(\theta)}{K_g(\theta + \Delta\theta)} = \left(\frac{U_s \theta}{U_s \theta + \Delta\theta} \right)^{0.523} \quad (3)$$

In this study the ratio of the time-averaged gas permeability coefficient, $\overline{K}_g(\theta)$, was calculated by using the time-averaged velocity.

RESULTS

Figure 4 displays the ensemble-averaged velocity vector fields surrounding the respiratory assist catheter taken at 80 and 60 ms after the initiation of the inflation period and deflation period, respectively. The legends in Figure 4 correspond to the magnitude of the velocity vectors. PIV velocity vector field showed the nonuniformity of the balloon-generated radial fluid velocity. The inflating balloon generated the outward radial motion at the top and bottom regions and tangential flow at the front and back regions. Similarly, the deflating balloon generated inward radial flow at the top and bottom regions and tangential flow at the front and back regions. The highest magnitude of the balloon-generated secondary flow approached 13 cm/s, which is on the order of the stream-wise average velocity.

The magnitudes of the ensemble-averaged radial velocity component of the fluid (see Equation 1) at four different angular points (top, bottom, front, and back) during the inflation and deflation periods are shown in Figure 5A and Figure 5B, respectively. The locations of the measurement points were approximately 1 to 2 mm from the outer fiber surface. The velocity measurements revealed that the inflating balloon did not generate radial fluid flow at the front and back points in the inflation period. The radial velocities at the top and bottom points were generated at 60 ms after the start of the inflation period and reached the highest magnitude of 6.7 cm/s. The balloon became fully inflated at 120 ms as the radial velocity vanished, and stopped inflating for the rest of the inflation period. In the deflation period, the radial velocity at the top and bottom points were generated at 20 to 30 ms after the initiation of the deflation period and lasted for about 60 ms. The difference of the time at which the radial velocity was generated is attributed to the operation of the pneumatic drive console. The PIV measurements showed that the radial velocity at the bottom points reached 7.4 cm/s and was higher than that at the top points for about 30 ms. Unlike the inflating balloon, the deflating balloon was shown to generate radial velocity as high as 5.6 cm/s at the back point, but this fluid motion lasted 30 ms shorter than that at the top and bottom points. Moreover, the sizes of the error bars, which indicate the magnitude of the root mean square (rms) velocity, started to increase as the radial flow was generated by balloon pulsation and reached a magnitude as high as 1.2 cm/s.

Figure 6 shows the ensemble-averaged radial velocity of the outer surface of the fiber bundle as a function of time during the inflation and deflation periods, respectively. The profiles of the fiber bundle radial velocities at the top and bottom points were similar to those of the fluid. The highest radial velocities of the fiber bundle at those two points reached magnitudes as high as 8.8 to 9.0 cm/s, which were higher than those of the fluid. Velocity measurements of the fiber bundle also revealed that balloon pulsation induced radial motion of the fiber bundle at the front and back points. The movement of the fiber bundle at the top and back points was always in the opposite direction of that at the front and back points. The highest root mean square velocity of the fiber bundle as shown by the error bars in Figure 6A and Figure 6B reached a magnitude as high as 0.7 cm/s, considerably smaller than that of the fluid.

The calculation of the time-averaged relative velocity in the inflation and deflation periods is displayed in Figure 7. The absolute magnitude of the relative radial velocity at different time steps were calculated by using Equation 1 and then Equation 2 was used to obtain the time-averaged relative velocity for a time period of 60 ms (between 60 and 120 ms after the initiation of the inflation period and between 20 and 80 ms after deflation period). The time-averaged relative velocity varied between 2.1 and 3.0 cm/s in the inflation period and between 2.0 and 3.2 cm/s in the deflation period.

To characterize the uniformity in the gas permeability coefficient, we normalized the gas permeability coefficient, $\overline{K_g(\theta)}$, at different angular locations with the maximal value of gas permeability coefficient, $\overline{K_g(\theta)_{\max}}$. Figure 8 displays the ratio of the time-averaged gas permeability coefficient, $\overline{K_g(\theta)/K_g(\theta)_{\max}}$, at different angular locations (top, bottom, front, and back points). Magnitudes of $\overline{K_g(\theta)/K_g(\theta)_{\max}}$ are the averaged values in the inflation and deflation periods. Two different velocities were used in Equation 3 to calculate the value of $\overline{K_g(\theta)/K_g(\theta)_{\max}}$. The highest variation in the gas permeability coefficient was about 49% to 59% (between top-bottom and front-back points) when time-averaged radial velocity (not shown) was used. The highest variation of $\overline{K_g(\theta)/K_g(\theta)_{\max}}$ at different locations was reduced, however, to 17% to 23% when the time-averaged relative radial velocity (see Figure 7) was used in Equation 3. This indicates that the movement of the fiber bundle was responsible for minimizing the variation of gas exchange permeability.

DISCUSSION

This study investigated the velocity pattern surrounding the respiratory assist catheter to explore whether the asymmetric balloon collapse would induce nonuniform, balloon-generated radial fluid motion surrounding the respiratory assist catheter and nonuniform gas permeability coefficient, or not. We found that the asymmetric balloon collapse created nonuniform radial fluid motion surrounding the respiratory assist catheter, and induced the movement of the fiber bundle. We also predicted the gas exchange permeability coefficient using the velocity data, and were able to show that the difference in gas permeability coefficient at four angular locations was reduced by the movement of the fiber bundle. It is important to investigate the spatial uniformity in the gas permeability coefficient for optimizing the performance of the respiratory assist catheter because any nonuniformity in gas permeability coefficient will lead to a lower gas exchange capacity of the respiratory assist catheter.

We compared our prediction of gas exchange permeability with the gas exchange data of Eash *et al.*¹¹ who has measured CO₂ exchange rates, V_{CO_2} , in four quarter regions by using helium as the sweep gas. Magnitude of gas permeability coefficient, K_{CO_2} , was approximated from CO₂ exchange rate, K_{CO_2} , by using the following equation:

$$K_{CO_2} = \frac{V_{CO_2}}{P_{CO_2}(\text{liquid}) - P_{CO_2}(\text{gas})} \quad (4)$$

where $P_{CO_2}(\text{liquid})$ and $P_{CO_2}(\text{gas})$ are average partial pressure of CO₂ in the liquid side and in the sweep gas side, respectively. The CO₂ partial pressure was calculated by averaging the inlet and outlet particle pressure of CO₂ (unpublished data). The variation of $K_{CO_2}/K_{CO_2\max}$ at pulsation frequency of 120 beats/min was calculated from the gas exchange rate data of Eash *et al.*¹¹ and the results were summarized in Figure 9. $K_{CO_2\max}$ is the maximal magnitude of K_{CO_2} observed at the "back" quarter region. The experimental study¹¹ showed a 16% to 19% variation in K_{CO_2} (16% to 20% variation in V_{CO_2}) among the four quarter regions. Comparison between Figure 8 and Figure 9 confirms that the relative velocity is the correct parameter to characterize the enhancement in the gas exchange rate of the respiratory assist catheter. The motion of the fiber bundle, which is generated by the nonsymmetric balloon, made the enhancement of gas exchange rate at different regions of the fiber bundle more uniform. Moreover, the measurement of K_{CO_2} performed by Eash *et al.*¹¹ was the average value for about 150 individual fiber membrane located in each quarter region, not individual fiber located at different angular points. If the magnitudes of the relative velocity in the regions between the two adjacent points are

assumed to be between those of the two points, then the predicted gas permeability coefficient will be more uniform and mimic more closely to K_{CO_2} data of Eash *et al.*¹¹

It is likely that the movement of the fiber bundle induced by the pulsating balloon is responsible for generating the secondary flow. This suggestion is also supported by the similarity in the temporal evolution of the radial velocity between the fiber bundle and the fluid. As the fiber bundle moves in the radial direction through the flowing fluid, it will disrupt the boundary layer created by the longitudinal flow and entrain some of the fluid into the fiber bundle. The entrained fluid will move in the opposite direction relative to the fiber movement, improving mixing interaction between the fiber and the fluid by bringing more fresh fluid into contact with the fiber. Moreover, the instantaneous velocity vector field confirmed the generation of tangential velocity at the front and back quarter regions (see Figure 4A and Figure 4B). The tangential velocity is generated by the confinement of the test section that limits the outward motion of the fluid. This tangential velocity component may provide another mechanism for improving fluid mixing, hence reducing the depletion of CO_2 concentration or the increase of O_2 concentration in the fluid near the fiber. The tangential velocity is also responsible for increasing the path length of the fluid flow surrounding the fiber bundle. These two mechanisms would provide additional enhancement in the gas exchange rate of the respiratory assist catheter.

Several parameters may affect the validity of the present results on gas permeability coefficient. The first parameter is the value of pulsation frequency, which is often varied to increase or reduce the gas exchange rate. Dynamic balloon volume measurements (unpublished results from our research group) performed by using a plethysmograph¹⁸ has confirmed that the inflation and deflation times of the balloon are not affected by the pulsation frequency as long as the pulsation frequency is less than the critical frequency, above which the balloon does not fully inflate and deflate. This indicates that the movement of the balloon surface is independent of the pulsation frequency. Therefore, the motion of the fiber bundle, the velocity pattern, and the uniformity of the gas permeability coefficient observed at different pulsation frequencies are expected to be similar to those observed at 120 beats/min. The second parameter is the volumetric flow rate of the fluid. Different cardiac output induces different blood volumetric flow rate in the vena cava, where the respiratory assist catheter is placed. An increase of water flow rate in an *in vitro* flow loop will increase the pressure on the balloon surface because pressure drop across the device increases with increasing volumetric flow rate. An increase in pressure drop is expected to increase the inflation time and to reduce the deflation time of the balloon because the volumetric flow rate of the gas used to fill the balloon is controlled by the pressure drop between the positive pressure and vacuum reservoirs in the pneumatic drive console and the balloon. As a result, the motion of the fiber bundle will become slower in the inflation period and faster in the deflation period. The change in the fiber bundle motion and the longitudinal velocity will change the magnitude of gas permeability coefficient at different regions of the fiber bundle, but we expect that the change in fiber bundle movement would occur uniformly so that a variation in volumetric flow rate of the fluid may not affect the uniformity of the gas exchange rate. The third parameter is the vessel size, which can vary depending on the size of the patients. Increasing the size of the vessel will have a similar effect as decreasing the volumetric flow rate of the fluid, and it is expected that the uniformity of the gas exchange will be independent of the vessel size. The fourth parameter is the balloon size, which has been shown by Hattler *et al.*¹⁹ to increase the gas exchange rate of the respiratory assist catheter. The increase in the balloon size is usually followed by an increase in the outer diameter of the fiber bundle and the pressure drop across the device. This indicates that increasing the balloon size will change the speed of the fiber bundle in the same way as increasing the volumetric flow rate and balloon. Moreover, increasing the balloon size will increase the inflation and deflation times because it will takes longer to fill

and empty a bigger balloon. This means that the duration when the radial velocity is generated (see Figure 4 and Figure 5) will be longer and this will lead to an increase in the gas exchange rate for the larger balloon size. If the balloon inflates and collapses the same way for different balloon sizes, we will expect that the uniformity of the gas permeability coefficient is independent of the balloon sizes. The use of different fluid will also affect the movement of the fiber and fluid. Besides increasing the pressure drop, fluid with higher viscosity (e.g., blood) will apply higher resistance (drag force) on the movement of the fiber. As a result, the speed of the fiber bundle movement in the blood will be slower than that in the water, producing smaller relative velocity and fluid velocity. We expect that change in fiber motion and the fluid induced by varying the fluid viscosity will not modify the uniformity in the relative velocity and the gas permeability coefficient.

Reducing the movement of the fiber bundle (increasing the relative velocity) or employing a catheter balloon that collapses symmetrically (generating the more uniform radial fluid velocity) may provide the modifications needed to enhance further the gas exchange rate of the respiratory assist catheter. But we feel that the improvement will not be significant enough to allow us to achieve our targeted gas exchange rate, which is 50% of the basal metabolic requirement (130 mL/min for CO₂ and O₂). We will shift our effort to a more promising device, rotational respiratory assist catheter, which incorporates the active mixing mechanism by rotating the whole fiber bundle. Preliminary experimental study has shown that the CO₂ and O₂ exchange rates per unit area were more than twofold greater than achieved in the same test using the pulsating respiratory assist catheters.²⁰

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Figure 1. Cross-sectional view of the nonsymmetric catheter balloon and the configuration of the four quarter regions and points used for the velocity measurements.

Figure 2.
Schematics of the *in vitro* flow loop and the respiratory assist catheter.

Figure 3. Particle image velocimetry unit (A) schematic (B) timing scheme for image acquisition.

Figure 4. Ensemble-averaged velocity vector field surrounding the respiratory assist catheter (A) at 80 ms after the initiation of the inflation period (B) at 60 milliseconds after the initiation of the deflation period.

Figure 5.

Ensemble-averaged radial velocity of fluid near the fiber bundle surface at axial distance of 20 cm from the proximal manifold (A) inflation period (B) deflation period.

Figure 6. Ensemble-averaged radial velocity of the fiber bundle at an axial distance of 20 cm from the proximal manifold (A) inflation period (B) deflation period.

Figure 7.
Time-averaged relative radial velocity between the fiber bundle and the fluid at an axial distance of 20 cm from the proximal manifold.

Figure 8.

Prediction of the normalized time-averaged gas permeability coefficient, $\bar{K}_g(\theta)/\bar{K}_g(\theta)_{\max}$, at different angular locations of the fiber bundle.

Figure 9.
The normalized gas permeability coefficient, $K_{\text{CO}_2}/K_{\text{CO}_2\text{max}}$, from the CO₂ exchange measurements of Eash *et al.*¹¹