Experimental Evaluation on Increasing the Efficiency of A Silicon Membrane Oxygenator

Kensuke ESATO*, Ron RICHARDS** and Ben EISEMAN**

*The Ist Surgical Division, Yamaguchi University School of Medicine, Ube, Yamaguchi, Japan

**Department of Surgery, Denver General Hospital and the University of Colorado Medical Center, Denver, Colorado, USA

(Received February 15, 1975)

Since membrane gas exchangers have been shown to be safer than oxygenators with a direct gas-blood interface[1),2)]. Various types of membrane oxygenators have been used clinically[3),4),5)]. But many problems remain to be clarified in the use of membrane oxygenators as a clinical tool. Of these problems, the most significant factor limiting usefulness of this device has been an insufficient oxygen transfer rate. Previously we described an effect for partial respiratory support and had a safe level well within acceptable limits[6),7)]. The purpose of the present paper is to evaluate the feasibilty of increasing the oxygen transfer rate using a recirculating circuit.

MATERIALS AND METHODS

This silicon rubber membrane oxygenator® is 28.6 cm long, 20.3 cm wide, 3.5 cm high. Priming volume of this unit is approximately 150 ml and the surface area of this unit is 0.75M^2. As diagrammatically illustrated (Figure 1), the extracorporeal circuit included a silicon rubber membrane oxygenator, two roller pumps, and one Travenol disposable heat exchanger. The circuit, made of 3/8 inch I. D. silastic tubing throughout, included a recirculating circuit between the arterial and venous reservoir. Oxygen gas flow in the oxygenator varied from 5–7 liters/minute. The unit was primed with 500 ml of Lactate Ringer solution plus 1000 ml of heparined blood collected from a single donor. Shim pressure in the oxygenator was kept at 150 mmHg to provide a constant thin blood film layer.

Evaluation of gas exchange by the oxygenator was undertaken using veno-arterial perfusion in 12 mongel dogs, weighting from 20 to 25 kilogr-

®Manufactured by the Travenol Laboratories, Morton Grove, Illinois.

ams. The dogs were anesthetized with sodium pentobarbital (30 mg per kilogram of body weight), and the inferior and superior vena cavae were cannulated via the right atrium after right thoracotomy. Cannulation of the right femoral artery was also performed. Venous blood was drained by gravity from both veins into the venous reservoir by the venous pump. The oxygenated blood was pumped into the right femoral artery by the arterial pump. The recirculating flow was determined by changing the venous pump flow, while the arterial pump flow was constant during perfusion.

The ratio of recirculating flow to arterial pump flow (RRF: APF) was calculated using the following formula:

$$\text{RRF: APF } (\%) = \frac{\text{Venous Pump Flow} - \text{Arterial Pump Flow}}{\text{Arterial Pump Flow}} \times 100$$

The RRF: APF of 0% expressed zero recirculating flow. The twelve dogs were divided into three groups. The first group of 2 dogs had arterial pump flows of 250 ml/min. during perfusion. In the first animal the venous pump flow was 250 ml/min (RRF: APF=0%), the second animal had a venous pump flow of 1250 ml/min (RRF: APF=400%).

The second group(5 dogs) and third group (5 dogs) were maintained at arterial pump flow rates of 500 ml/min. and 750 ml/min. respectively, whereas RRF: APF was adjusted at rates of 0%, 100%, 300% and 400% in both groups by controlling the venous pump flow. Duration of each perfusion was two hours and all the animals were mechanically ventilated with room air using the Harvard respirator. Heparin was administered in a dose of 2mg per kilogram of body weight before cannulation.

The arterial pump flow was measured by a probe monitoring through a B.L.I. pulse logic flowmeter (Biotronex Laboratory, Inc., Silver Springs, Maryland) and the venous pump flow calibrated by rotating rate before perfusion. Venous blood samples were drawn from the venous line just proximal to the venous reservoir (Point A-Figure 1) and arterial blood samples were obtained from the arterial line downstream from the arterial pump (Point B-Figure 1) at 15 minute intervals.

Rectal temperature was maintained at 37° ± 2°C by the heat exchanger. Pressure catheters were placed in the left femoral artery and the inferior vena cava. Arterial pH was corrected to 7.4 with $NaHCO_2$ as necessary. Partial pressure of oxygen and carbon dioxide and pH were measured and oxygen saturation calculated. Hemoglobin in both whole blood and plasma and hematocrit were also determined. Oxygen and carbon dioxide transfer rate were calculated by methods described previously.[8)]

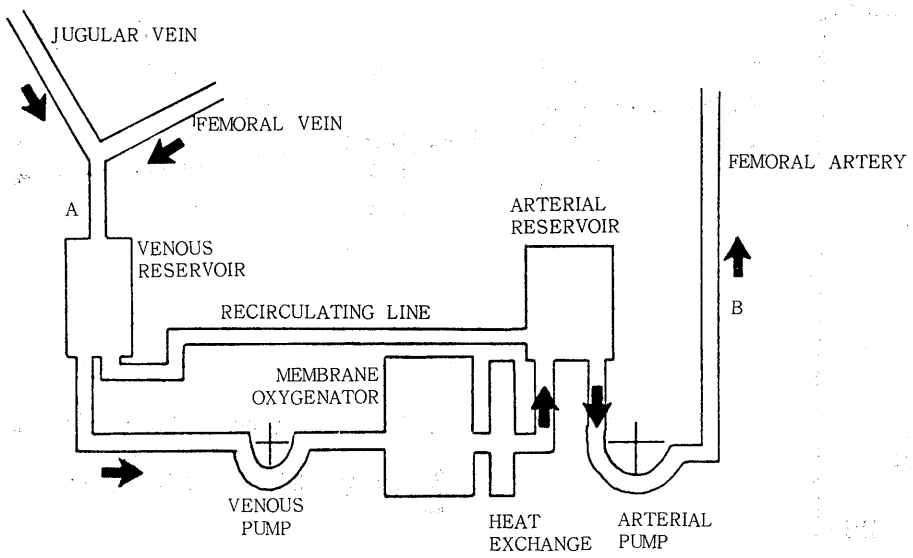


Figure 1. Circuitry for Evaluation of Oxygenator

RESULTS

Effect of RRF: APF on the output saturation is shown in Figure 2. Throughout RRF: APF from 0% to 400%, output oxygen saturation paralleled input saturation and no significant difference was detected. Figure 3 demonstrates the change of the % saturation difference across the oxygenator (ΔSO_2) at the various of recirculating flow to arterial pump flow. At arterial pump flow of 750 ml/min, the mean values of ΔSO_2 increased, as RRF: APF elevated. Comparing ΔSO_2 between RRF: APF of 0% and 400%, ΔSO_2 at RRF: APF of 400% had a highly significant increase ($p<0.05$).

Because input saturation of RRF: APF of 0% was 69.1 ± 4.5%, whereas that of RRF: APF of 400% was 34.0 ± 1.4%, it was not clear whether there was significant difference in ΔSO_2 between RRF: APF of 0% and 400%.

At arterial pump flow of 500ml/min., there was no difference in ΔSO_2.

Effect of the ratio of recirculating flow to arterial pump flow on the oxygen transfer rates is shown in Figure 4. Oxygen transfer rates were constant through any RRF: APF at arterial pump flow rates of 500ml/min. At arterial pump flow of 750ml/min., oxygen transfer rates increased in proportion to the RRF: APF, although there was no statistically significant difference with and without recirculation. There was no evidence from this

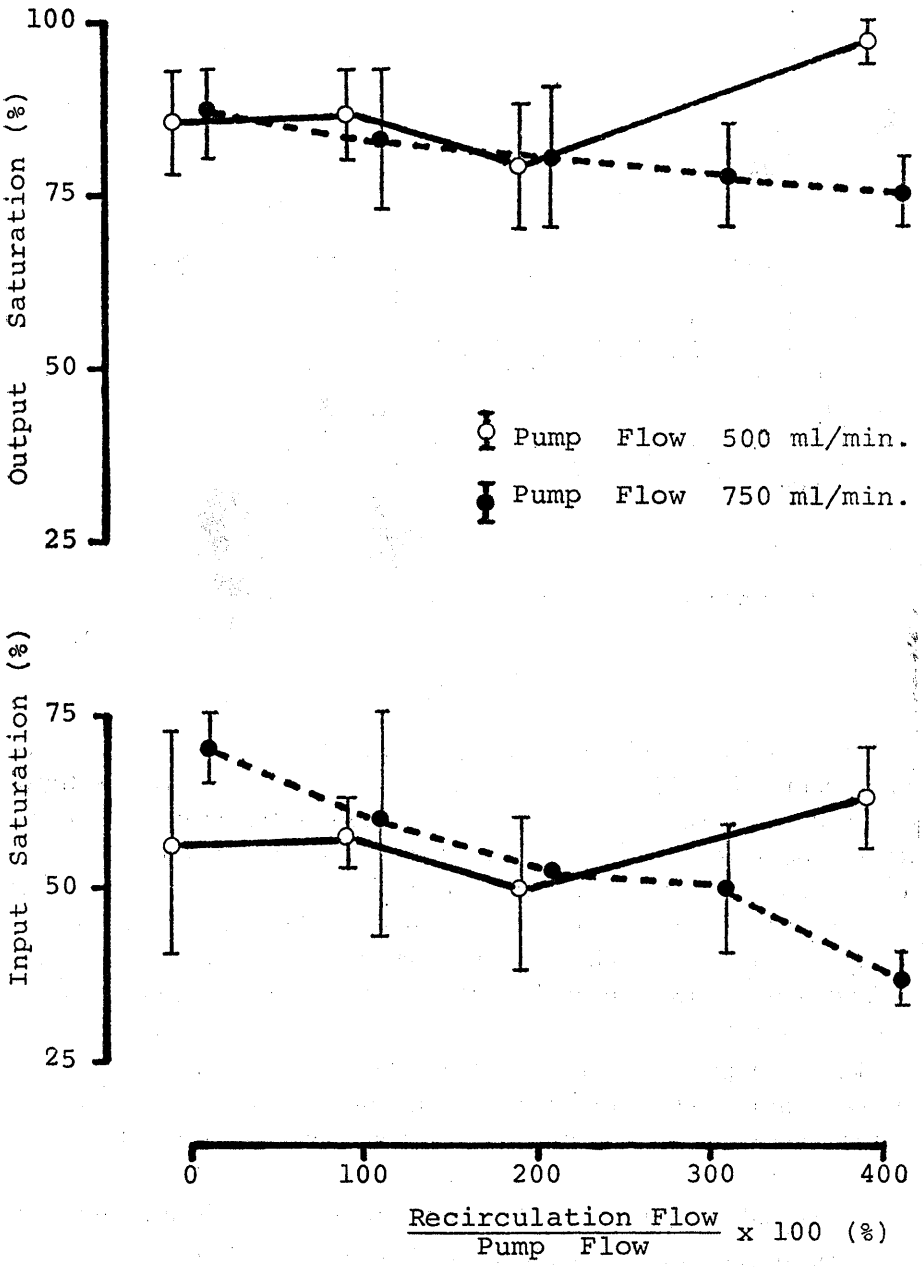


Figure 2. Effect of Ratio of Recirculation Flow to Pump Flow on the Output Saturation. Hematocrit 35-46%

data to support the concept that recirculation was effective in increasing the oxygen transfer rates at arterial pump flows of 500 ml/min. and 750 ml/min.

Figure 5 demonstrates the effect of recirculation at RRF: APF of 400%, on the oxygen transfer rates with the various arterial pump flows. At arterial pump flows of 500ml/min. and 750 ml/min., there is no significant difference in the oxygen transfer rates with and without recirculation.

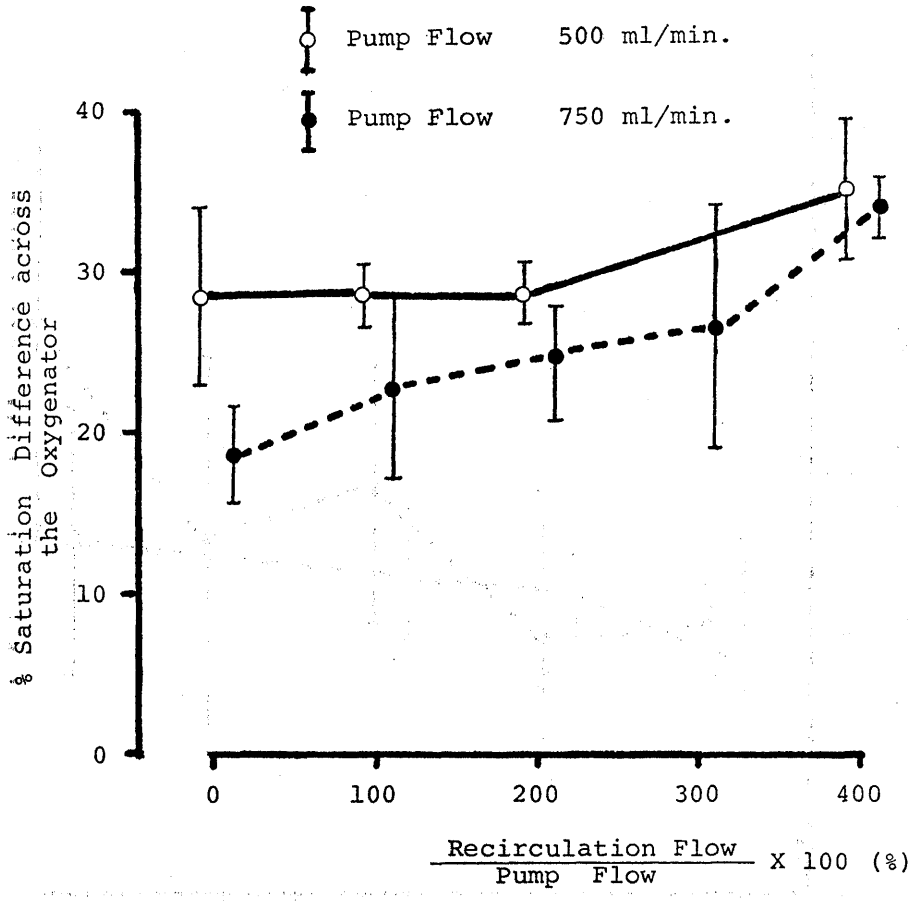


Figure 3. Change of the Saturation Difference across the Oxygenator at the Various Ratio of Recirculation Flow. Hematocrit 35-46%, Input Saturation 34-69%

At arterial pump flows of 250 ml/min, however, the oxygen transfer rate with recirculation had a mean value of 23.2 ml/min ± standard error of the mean 4.2 ml/min., significantly higher than without recirculation which was 6.2 ± 3.9 ml/min. ($p<0.01$). This finding will be discussed later.

Table 1 shows the changes of the carbon dioxide transfer rates at the various ratios of recirculating flow to arterial pump flow. This value varied a great deal, and constant relationship with and without recirculation was not found.

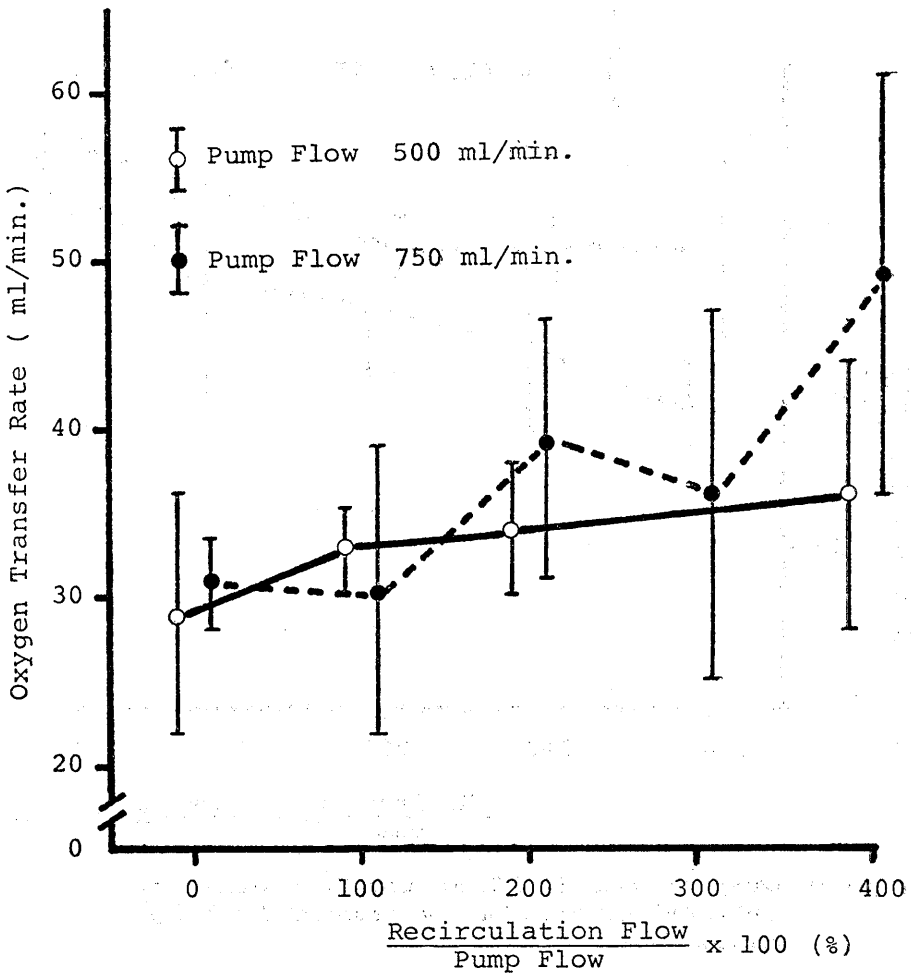
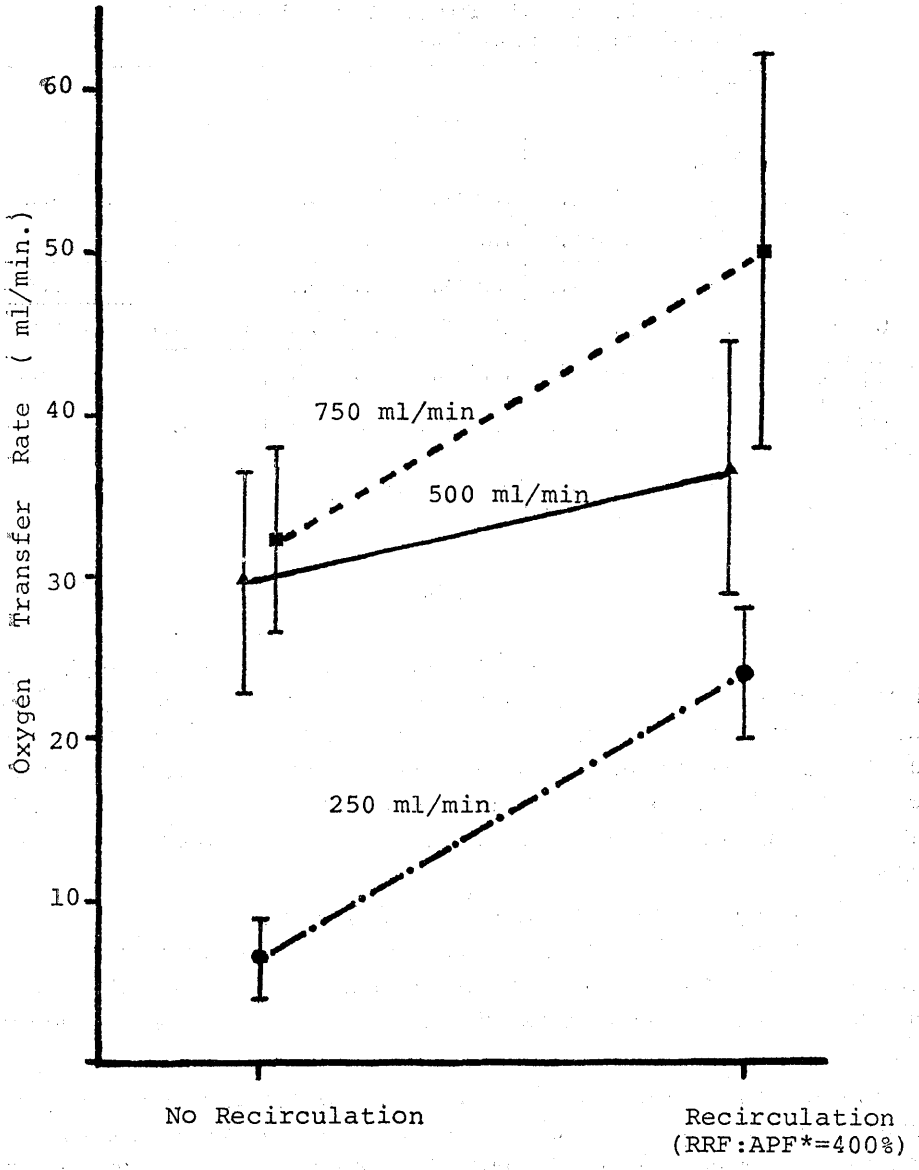


Figure 4. Effect of Ratio of Recirculation Flow to Pump Flow on the Oxygen Transfer Rate. Hematocrit 35-46%, Input Saturation 34-69%



*Ratio of Recirculation Flow to Pump Flow

Figure 5. Effect of Recirculation on the Oxygen Transfer Rate, Hematocrit 36-46%, Input Saturation 34-61%

Table 1. Change of Carbon Dioxide Transfer at the Various Ratio of Recirculation Flow to Pump Flow

	RRF-APF* (%) / APF** (ml/min.)	0	100	200	300	400
Input PH	500	7.23±0.09	7.48±0.02	7.31±0.06		7.43±0.01
	750	7.38±0.08	7.35±0.02	7.38±0.03	7.12±0.1	7.11±0.01
Input PCO_2 (mmHg)	500	56.1±4.7	25.8±2.3	37.8±6.7		33.2±1.0
	750	41.6±9.2	31.0±2.6	30.6±4.2	56.1±11.7	69.2±1.4
Carbon Dioxide Transfer Rate (ml/min.)	500	49.1±13.9	72.6±6.8	34.3±16.3		80.9±16.2
	750	141.5±15.1	81.9±24.0	82.9±6.4	72.0±4.1	126.0

*RRF: APF: Ratio of Recirculation Flow to Pump Flow
**APF: Arterial Pump Flow

DISCUSSIONS

The absence of a direct blood-gas interface in membrane oxygenator offers distinct advantages over the disc and bubble oxygenators. These advantages include lower levels of hemolysis, decreased sublethal red blood cell damage, and diminished protain denaturation. However, the major deficiency of the membrane oxygenator is an insufficient oxygen transfer rate. To improve oxygen transfer rate, various methods have been reported:

1) Reducing blood film thickness to the minimum[9]; 2) using a recirculating circuit in which blood is recirculated several times before it is pumped to the patient[10]; 3) promoting turbulence in the liquid phase by inclusion of baffles, such as Saran Screens[11]; and 4) rotating the membrane[12].

In the Travenol silicon rubber membrane oxygenator, it is possible to control the thickness of the blood film layer on the membrane by shim pressure. According to Boyd's report[1], levels below 120 or greater than 200 mmHg of shim pressure is deleterious and significantly interferes with oxygen transfer rate.

In this erperiment a recirculating circuit was utilized in an attempt to the oxygen transfer rate. From our data, there is no statistically significant difference of oxygen transfer rate with and without recirculation at arterial pump flows of 500 ml/min., and 750 ml/min. However, at arterial pump flow of 250 ml/min., oxygen transfer rate with recirculation in which

RRF: APF is 400% is significantly higher than that without recirculation. The following mechanism is suggested. Figure 6, from Trudell[13], demonstrates thermistor output traces following the injection of a constant bolus of ice saline in the circuit of an oxygenator perfused at three different flow rates without recirculation. At low flow rates of 285 ml/min. through the 0.75 M^2 Travenol membrane oxygenator, both with and without the shim being pressurized, there is a shunt (at arrow) in the blood phase. As the flow rates increase, a shunt continues to exist when the shim is not pressurized but largely disappears with the shim pressurized.

Based on these findings, it is important to use a circuit in which blood is recirculated several times to correct a shunt which occurs at the membrane-blood interface at low flow (250 ml/min.) when venous blood is not completely oxygenated after a single pass through the oxygenator.

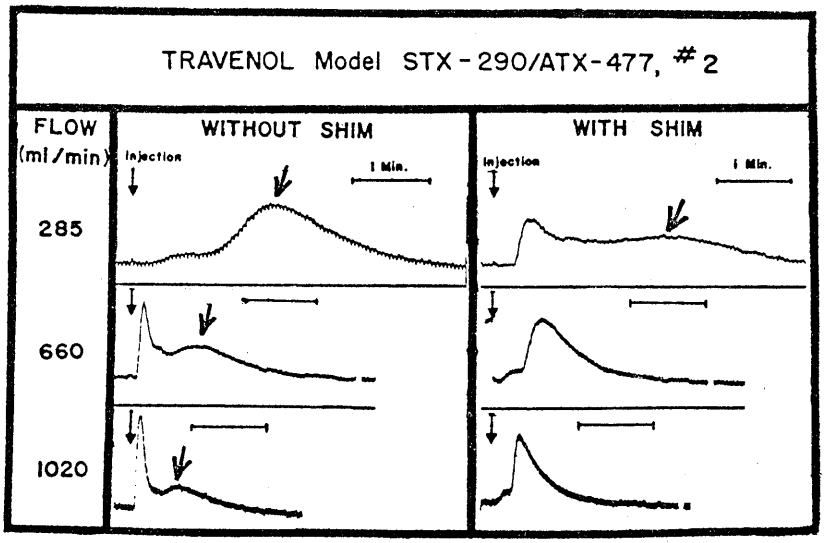


Figure 6. Thermistor Output Traces Following the Injection of a Constant Bolus of Ice Cold Saline in the Blood Circuit of an Oxygenator Perfused at 3 Different Flow Rates without Recirculating Flow (quoted from Trudell, L.A.[13]).

CONCLUSIONS

Experiments on 12 dogs were performed to evaluate oxygen transfer rate using the recirculating circuit.

1) At arterial pump flow rates of 500 ml/min. and 750 ml/min., there is not statistically significant difference in the oxygen transfer rates with or without recirculation.

2) At arterial pump flow rates of 250 ml/min., oxygen transfer rates with and without recirculation, when the ratio of recirculating flow to arterial pump flow is 400%, are 23.2 ± 4.2 ml/min. and 6.2 ± 3.9 ml/min. respectively suggesting the benefit of recirculation at low flow rates.

3) It is necessary to use a recirculating circuit at low flow rates in order to increase the efficiency of the silicon rubber me nbrane oxygenator. At high flow rates, no benefit is detected.

This paper will be in press in the J. Thoracic & Cardiovas. Surg.

REFERENCES

1) Boyd, J. C., Moran, J. F. and Clark, R. E.: An Analysis of the Operating Characteristics of the 0.25 M². Travenol Infant Membrane Oxygenator. *Surg.*, 71 : 262, 1972.
2) Zotti, E. F., Ikeda, S., Lesage, A. M., Sealy, W. C. and Young, W. G. Jr.: Prolonged Veno-Venous Perfusion with a Membrane Oxygenator for Respirator Failure. *J. Thoracic & Cardiovas Surg.*, 51 : 383, 1966.
3) Carlson, R. G., Landè, A. J., Ivey, L. A.., Subramnian, V. A., Block, J. H., Rogos, B., Landis, B., Baxter, J., Patterson, R. H., and Lillehei, C. W.: The Landè-Edwards Membrane Oxygenator for Total Cardiopulmonary Support in 110 Patients during Heart Surgery. *Surg.*, 72 : 913, 1972.
4) Sugg, W. L., Fenning, J. S., Platt, M. R.: Heart Surgery a Membrane Oxygenator in Infants. *J. Thoracic & Cardiovas. Surg.*, 67 : 593, 1974.
5) White, J. J., Anderson, H. G., Risemberg. H., Mazur, D., Haller, J. A. Jr.: Prolonged Respiratory Support in Newborn Infants with a Membrane Oxygenator. *Surg.*, 70 : 288, 1971.
6) Birnbaum, D. and Eiseman, B.: Laboratory Evaluation of a New Silicon Membrane Oxygenator. *J. Thoracic & Cardiovas. Surg.*, 64 : 441, 1972.
7) Douglas, M., Birnbaum, D. and Eiseman, B.: Biological Evaluation of a Disposable Membrane Oxygenator. *Arch. Surg.*, 103 : 89, 1971.
8) Esato, K. and Eiseman, B.; Experimental Evaluation of Gore-Tex Membrane Oxygenator. *J. Thoracic & Cardiovas. Surg.*, 69 : 690, 1975.
9) Richardson, P. D., Snider, M. T. and Galletti, P. M.: Oxygen Transfer to Blood in Membrane Lungs; Correlation and Prediction from in Vivo Measurements. *Trans. Amer. Soc. Artif. Int. Organs.*, 17 : 323, 1971.
10) Landè, A. J., Parker. B., Subramanian, V. A. Carlson, R. G., Lillehei, C. W.: Methods for Increasing the Efficiency of a New Dialyzer-Membrane Oxygenator. *Trans. Amer. Soc. Artif. Intern. Organs.*, 14 : 227, 1968.
11) Marx, T. I., Baldwin, B. R., and Miller, D. R.: Factors Infuencing Oxygen Uptake by Blood in Membrane Oxygenator. *Ann. Surg.* 156 : 204, 1962.
12) Ratan, R. S., Bennett, G. F., Bollin, P. L., McAlpine, W. A. and Selman, M. W.: Experimental Evaluation of a Rotating Membrane Oxygenator. *J. Thoracic & Cardiovas. Surg.*, 53 : 519, 1967.
13) Trudell, L. A., Friedman, L. I., Kakvan, M., Galletti, P. M. and Richardson, P. D.: Evaluation of a Disposable Membrane Oxygenator. *Trans. Amer. Soc. Artif. Int. Organs.*, 18 : 538, 1972.