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A Newly Designed Pneumatic Pulse Pump Membrane Oxygenator

S. Hashimoto, *S. Tominaga, †M. Yoshida, and †Y. Sasaki

*Departments of Bioengineering and *Thoracic Surgery, School of Medicine, Kitasato University; and †Materials Department, Engineering Division, NOK Corporation, Kanagawa, Japan*

Abstract: In order to shorten the extracorporeal circulation circuit and to increase the efficiency of oxygenation, a new membrane oxygenator combined with a pump was designed. The membrane was formed with a silicone tube (0.3 mm internal diameter, 0.64 mm external diameter). In the miniature model, 1,700 pieces (200 mm length each) of tube were bundled and packed in a polycarbonate-cylinder with elastic silicone fillers. In both inflow and outflow sides of the cylinder, ball valves were equipped. The total available area of the membrane is 0.19 m^2. In this model, the membrane was pneumatically driven with the reciprocating pump in performance tests, in which 100% oxygen circulated in the gas side (outside of the tube). The compliance test shows that a 7% decrease in the volume of blood side (inside of the tube) is made by a 0.5 atm pressure difference across the membrane. The gas permeability test shows that 13.5 ml/min oxygen gas is permeated by 0.5 atm pressure difference at 24°C. The mock test shows that the oxygen tension increases from 118 mm Hg at the inlet to 354 mm Hg at the outlet of the oxygenator when 12 ml/min (0.2 ml stroke volume) saline solution is pumped. The performance has been maintained in animal tests. **Key Words:** Membrane oxygenator—Pneumatic pulse pump membrane oxygenator.

In order to shorten the extracorporeal circulation circuit and to increase the efficiency of oxygenation, new membrane oxygenators combined with the pump were designed.

METHODS

Two types of pneumatic pulse pump membrane oxygenators were manufactured: one of sheet and one of tubes. In the former type, a silicone sheet (0.032 cm thick, 260 cm^2 available area for gas exchange) is held between two parts of a polymethylmethacrylate housing (80 cm^3 liquid side volume) (Fig. 1). In the latter type (model 1–5 in Fig. 2), 10–1,700 pieces (14–20 cm length each) of tube are bundled and packed in a polycarbonate cylinder housing (a glass cylinder is used only in the model 3) with elastic silicone fillers (Table 1). In both inflow and outflow sides of the blood flow path of the housing, one-way valves (nylon ball) are equipped. In model 5, the filling volume from the inlet valve to the outlet valve is 37 cm^3. The membrane is pneumatically driven with a positive-pressure respirator so that the housing simultaneously plays two roles: the oxygenator and the pump. In the pumping test, the membrane was driven by alternatively changing pressure (Fig. 3). In mock tests, saline solution (24°C), in which carbon dioxide tension was elevated to 45–65 mm Hg, was introduced. For the comparative test of the gas permeability, a roller pump was used to impel the saline solution without membrane pumping (Fig. 4). In animal tests, adult mongrel dogs (weighing 15–17 kg) were used. In the gas side (the one side of the sheet or the outside of the tube), 100% oxygen gas was circulated. In the case of the sheet type model (Fig. 5), the heparinized blood was drained from the inferior vena cava and infused into the superior vena cava. In the case of model 5 (tube type, Fig. 6), the blood was drained from the femoral vein (via silicone tube of 0.3 cm internal diameter) and infused into the jugular vein (via polyethylene tube of 0.2 cm internal diameter). The flow rate at the outlet of the oxygenator was measured by an electro magnetic flow meter (Fig. 7). The permeability coefficients (k) of oxygen and of carbon dioxide are calculated by

Address correspondence and reprint requests to Dr. S. Hashimoto, Department of Bioengineering, School of Medicine, Kitasato University, 15-1, Kitasato 1-Chome, Sagamihara-shi, Kanagawa, 228 Japan.

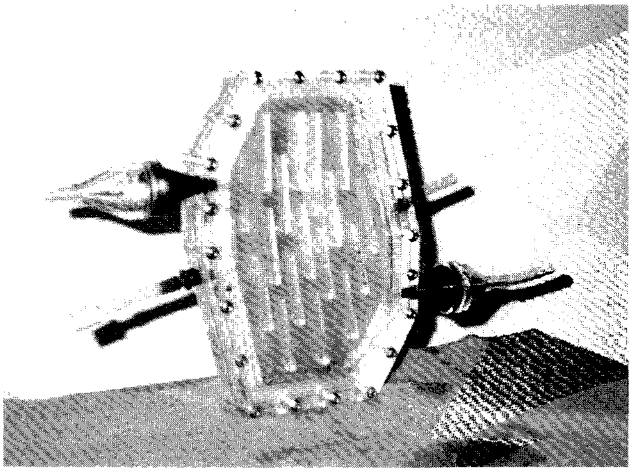

FIG. 1. Pneumatic pulse pump membrane oxygenator in sheet type.

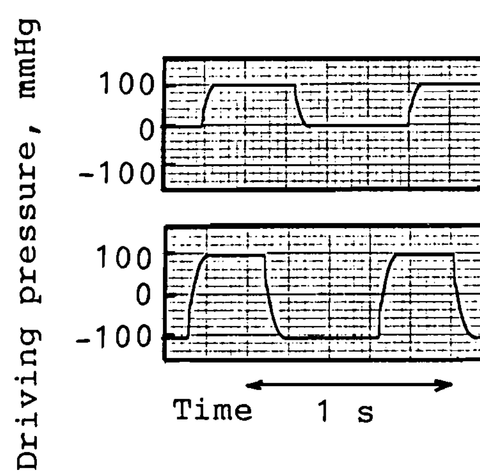

FIG. 3. Driving pressure tracings in the mock test.

TABLE 1. *Pneumatic pulse pump membrane oxygenator in tube type*

Model	Di(cm)	De(cm)	Lt(cm)	Lg(cm)	Np	Ag(cm^2)	Vg(cm^3)
1	0.147	0.196	17	11	10	51	1.9
2	0.147	0.196	19	12	210	1,200	43
3	0.030	0.064	15	12	600	680	5.1
4	0.030	0.064	20	12	1,700	1,900	14
5	0.030	0.064	14	5.5	1,700	880	6.6

Di, internal diameter; De, external diameter; Lt, total length of each tube; Lg, available length of each tube for gas exchange; Np, number of pieces of tube; Ag, integrated available-internal-area of tubes for gas exchange (Ag = Np π Di Lg); Vg, integrated available-internal-volume of tubes for gas exchange and pumping (Vg = Np π Di^2 Lg/4).

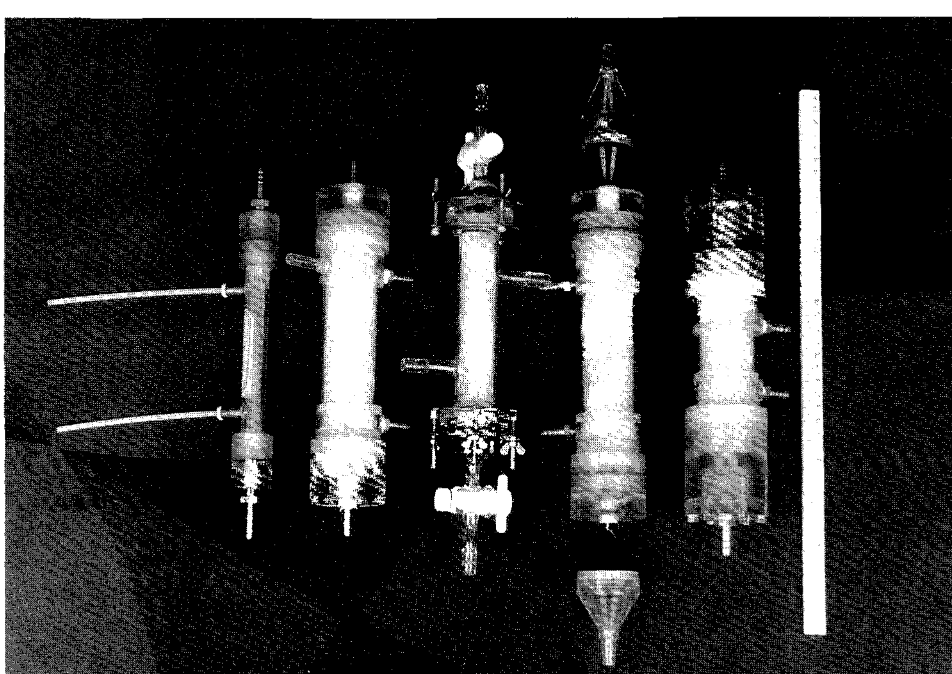

FIG. 2. Pneumatic pulse pump membrane oxygenator in tube type: models 1, 2, 3, 4, 5 (from left to right). In models 1–3, one-way valves are removed. In model 5, ball valves are built-in.

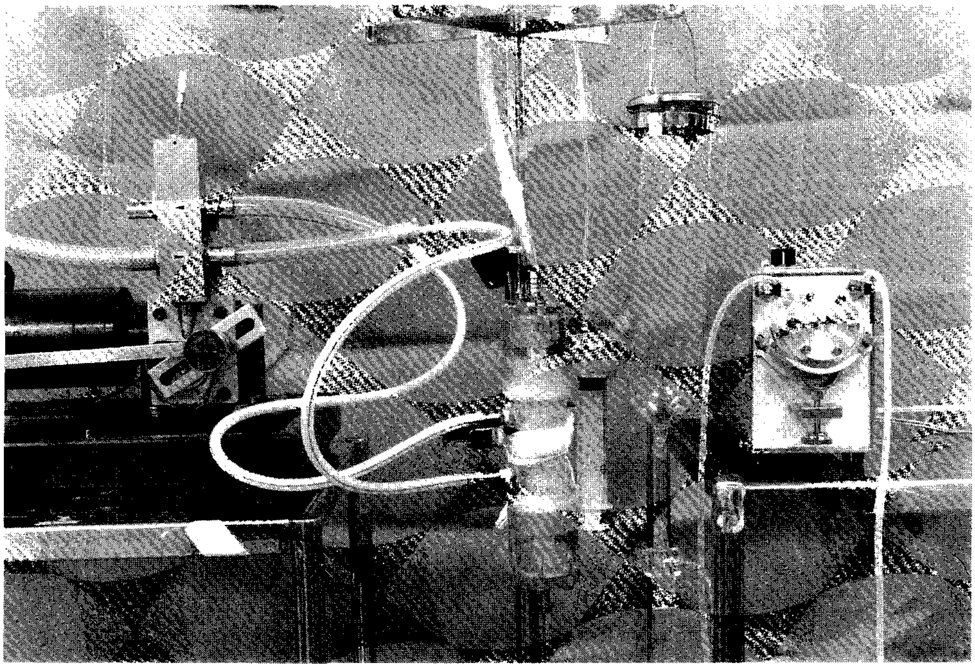

FIG. 4. Mock circuit: respirator (left), pneumatic pulse pump membrane oxygenator (middle), roller pump (right). The roller pump is used only in comparative tests (see text).

$$k = q\,(x/p)/Ag, \qquad (1)$$

where q is permeated gas flow-rate (cm^3/s), x is thickness of the membrane (cm), p is the pressure difference (dyn/cm^2), Ag is the available area for gas exchange (cm^2).

RESULTS

The compliance tests in models 4 and 5 show that a 7% decrease in the volume of blood side is made by a pressure difference of 380 mm Hg across the membrane. The pumping test at 24°C in model

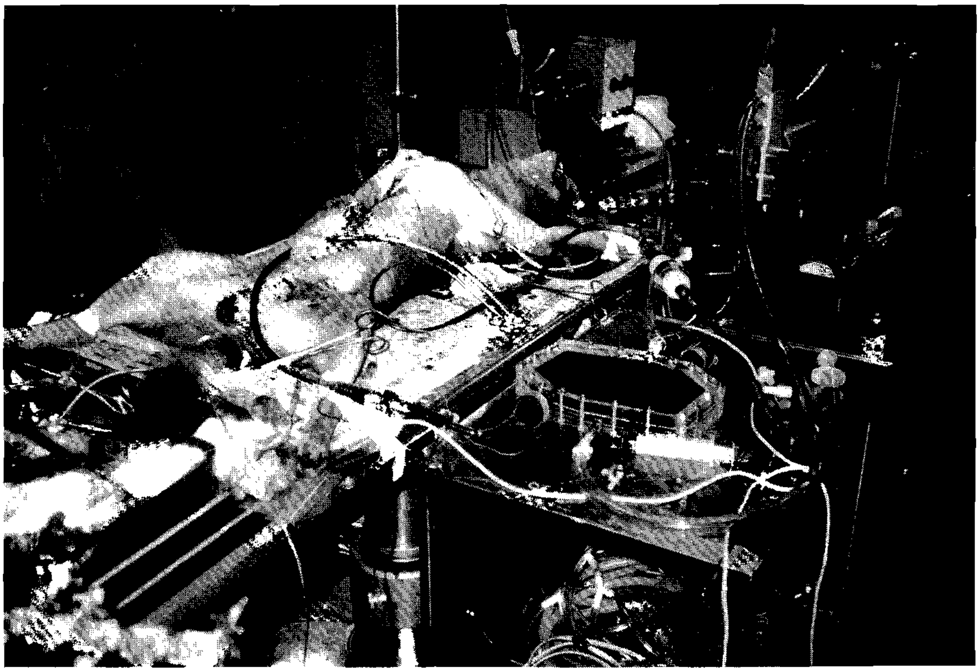

FIG. 5. Animal test with sheet type.

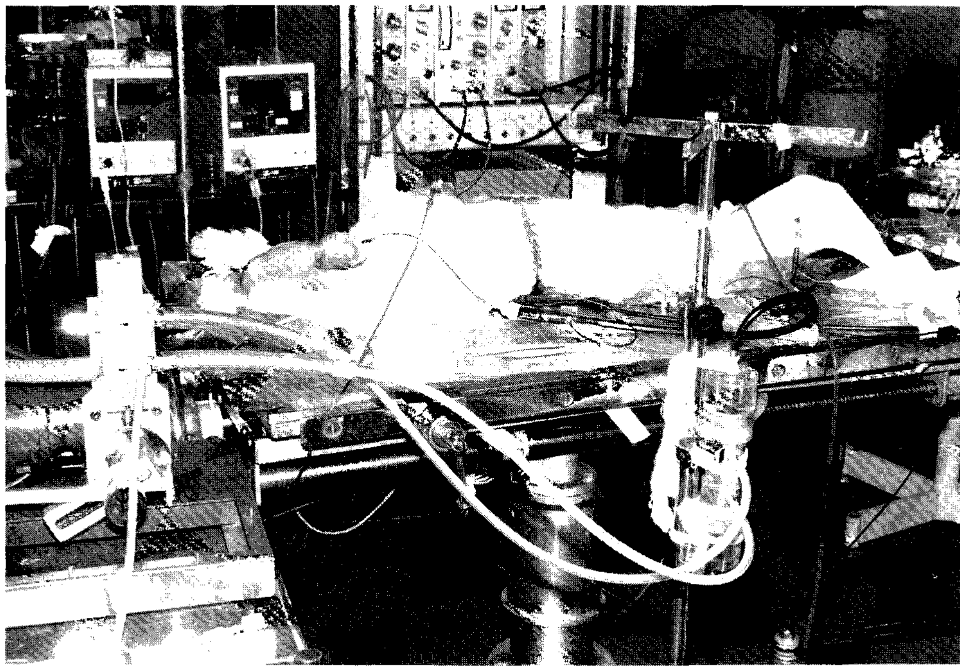

FIG. 6. Animal test with tube type (model 5).

5 shows that alternatively changing (60 min^{-1}) driving pressure (Pr) of 0 or 100 mm Hg impels 7 ml/min of water and that Pr of −100 or 100 mm Hg impels 17 ml/min of water (Fig. 3) when the inlet and outlet pressures are 0 and 20 mm Hg, respectively. The gas permeability tests in the gas phase in models 3–5 show that *k* of oxygen is 4×10^{-12} cm^4 dyn^{-1} s^{-1} with pressure difference of 380 mm Hg at 24°C. Tensions of oxygen and carbon dioxide in mock and animal tests are exemplified in Table 2. The permeability coefficients (*k*) in mock and animal tests are summarized in Table 3. The mock tests show that *k* is larger in membrane pumping than in roller pumping (compare data of saline solution in Table 3). The animal test in the tube type showed that *k* was maintained even when 100% oxygen gas changed to the air in the gas side. When the inlet pressure was 10 mm Hg, 150–400 ml/min of blood was able to be pumped with membrane pumping in the sheet type, and 6–12 ml/min of blood was able to be pumped in the tube type. Figure 7 shows regurgitation at the ball valve (in the model 5).

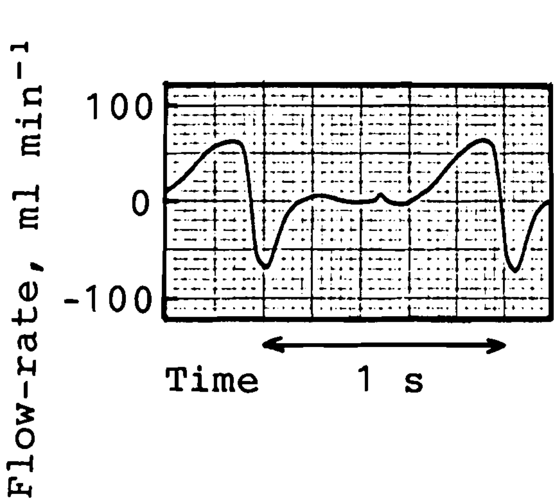

FIG. 7. Flow rate tracing in the animal test with tube type (model 5).

DISCUSSION

In the sheet type, fairly good pumping was performed. In this model, however, the position of the membrane sheet was unstable, and the compliance of the membrane was so large that membrane rupture occurred. To solve the problem, the sheet type was changed to the tube type. In models 1–3, regurgitation occurred between the potting filler and the housing cylinder. In models 4 and 5, the stiffness of the cylinder was modified to match with that of the potting filler. The mock test shows that the gas permeability increases by pulsation of flow in the pneumatic pulse pump membrane oxygenator. This result is consistent with the previous study (1). To increase the shear rate at the tube wall (from the model 1 to 5), flow rate increased with a de-

TABLE 2. *Tensions of oxygen and carbon dioxide in mock and animal tests*

Model	Liquid	PiO_2	PoO_2	$PiCO_2$	$PoCO_2$	Ql	Vs	Qg
		mm Hg	mm Hg	mm Hg	mm Hg	ml/min	ml	L/min
sheet	blood	18	19	48	40	400	20	7
5	saline	118	354	56	31	12	0.2	9
5[a]	saline	127	326	47	35	12	—	9
5	blood	49	510	31	26	6	0.1	6

[a]Liquid impelled not with the membrane pumping, but with the roller pump equipped in the inlet line of housing (see Figs. 1, 2 and Table 1); PiO_2, oxygen tension at inlet; PoO_2, oxygen tension at outlet; $PiCO_2$, carbon dioxide tension at inlet; $PoCO_2$, carbon dioxide tension at outlet; Ql, liquid flow-rate; Vs, liquid stroke volume; Qg, gas flow-rate.

TABLE 3. *Summarized data from animal tests and mock tests*

Model	Liquid	Ql	kO_2	kCO_2
		ml/min	$cm^4\ dyn^{-1}\ s^{-1}$	$cm^4\ dyn^{-1}\ s^{-1}$
sheet	blood	150–400	$(6 \pm 2) \times 10^{-12}$	$(2 \pm 4) \times 10^{-10}$
5	saline	12	3.9×10^{-14}	1.5×10^{-12}
5[a]	saline	12	3.2×10^{-14}	0.8×10^{-12}
5	blood	6–12	$(2 \pm 1) \times 10^{-13}$	$(1 \pm 1) \times 10^{-12}$

[a]See Table 2. Model, see Figs. 1, 2 and Table 1; Ql, liquid flow rate; kO_2, permeability coefficient of oxygen; kCO_2, permeability coefficient of carbon dioxide.

crease of flow resistance (shorten the tube length) and the internal diameter decreased. The calculated shear rates at the tube (0.015 cm internal radius) wall are 22 s^{-1} for 6 ml/min mean flow rate and 220 s^{-1} for 60 ml/min maximum flow rate (Fig. 7) in Poiseuille flow. A shear rate of $> 400\ s^{-1}$ is desirable to inhibit clot formation (2).

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