[Henry Ford Hospital Medical Journal](https://scholarlycommons.henryford.com/hfhmedjournal)

Volume 6 | Number 4 Article 9

12-1958

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EXPERIMENTAL STUDIES WITH LOW OXYGEN FLOW RATES IN THE BUBBLE OXYGENATOR

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Accumulated clinical and experimental experience with extra-corporeal circulation has led to the solution of many of the problems which initially confronted workers in this field. However, in many centers where cardio-pulmonary by-pass is utilized for open heart surgery, a certain number of "cerebral deaths" have occurred early in the postoperative period. This syndrome frequently presents a fairly constant pattern of an immediate lucid interval followed by agitation, depression, coma and death occurring 12 to 72 hours postoperatively. This complication has been observed to follow the use of several types of oxygenators. Many causal factors have been suggested and investigated. Although oxygen toxicity and gas embolism have not been demonstrated as etiologic agents responsible for this syndrome, it is entirely reasonable to suspect these causes and attempt to eliminate or minimize them.[1] The investigations herein reported were designed to establish the minimum oxygen flow rates in the DeWall-Lillehei bubble oxygenator which would produce satisfactory oxygenation of the blood and at the same time prevent excessive amounts of physically dissolved oxygen in the plasma. Unphysiologic arterial oxygen partial pressures would thereby be avoided in the perfused blood, which if sufficiently high, could produce gas embolism. Additional advantages would consist of decreased trauma to the blood in the oxygenator and simplified defoaming in the debubbling chamber.

Clark and co-workers[2] have reported the polarographic monitoring of blood oxygen tension as a means to insure adequate oxygenation while avoiding over saturation of the perfused blood. Since it has been determined that the plasma oxygen partial pressure does not exceed 200 mm. of Hg. (normal 100 mm. of Hg.) until 98.8% saturation is reached, excessive oxygen tensions would be avoided by saturation levels below this point.[3,4] Provided that oxygenator efficiency could be approximately determined, a suitably low oxygen flow rate could be used in the oxygenator which would produce saturation levels sufficient to supply body oxygen needs and result in a more physiologic perfusion. A constant oxygen tension monitoring device would then be unnecessary.

Accordingly, a series of experiments were designed to establish if possible, a relationship between optimal oxygenation, oxygen flow rates related to body weight, perfusion rate and size of oxygenator components.[5] Total cardio-pulmonary by-pass was carried out on several series of dogs weighing between 9 and 15 kilograms. The

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DeWall-Lillehei unit and Sigmamotor pump were utilized in all experiments. Anesthesia was induced with intraperitoneal Nembutal and exposure obtained through a bilateral trans-sternal, fourth interspace thoracotomy. Arterial inflow was through the left subclavian artery. Cannulae in the inferior and superior vena cavae were brought out through the right atrium and drained into a reservoir by gravity. Aortic, central venous pressures, rectal temperature, and blood pH were monitored. Oxygen saturations were determined by photoelectric cell and content by VanSlyke method. Samples for these studies were drawn simultaneously from arterial and venous lines at periodic intervals during the by-pass. During the course of each perfusion, the endotrachael tube was occluded. Oxygen metering valves having a maximum flow rate of eight liters/min. were utilized for accuracy in measuring the small flow rates.

RESULTS

In the first series of experiments, (Table 1) 10 dogs were perfused at blood flow rates of 30, 50, and 70 cc/kg./min., and oxygen flow rates of 2, 3, 5, and 7 liters/min., for each liter of blood flow. In reviewing the results of this group, normal

Bl. Flow		O_2 Flow		Temp.		B.P.		Art.		Ven.		
cc/Kg/min.	Total	Ratio	Total	Rectal	Water bath	Art. mm.Hg.	Ven. Cm. H_2O	O2 Cont.	Sat.	O2 Cont.	Sat.	A-V diff.
30	420	2/1	1.0	94	110	50	-5	16.1	86	8.1	43	8.0
30	420	5/1	2.0	93	110	48	-1	17.9	95	7.8	41	10.1
30	420	7/1	3.0	94	112	57	-1	17.8	95	7.1	38	10.7
50	700	2/1	1.5	94	107	90	+6	15.8	84	8.6	46	7.2
50	700	5/1	3.5	94	112	85	-1	17.7	94	9.6	51	8.1
50	700	7/1	5.0	93	110	85	0	18.4	98	10.8	58	7.8
70	980	2/1	2.0	94	112	105	+3	17.3	92	11.7	62	5.6
70	980	5/1	5.0	93	113	98	-1	18.6	99	13.4	71	5.2
70	980	7/1	7.0	93	110	100	+1	18.6	99	15.6	83	3.0

Table I

Table 1

Representative data obtained from 10 perfusion experiments which were carried out at various blood and oxygen flow rates.

arterial and venous oxygen saturations (and therefore normal A-V differences) occurred at a perfusion rate of 70 cc./kg./min., with a ratio of 2.2 liters of oxygen for each liter of blood flow (ratio of 2.2:1). Normal arterial oxygen saturation levels were produced by a perfusion rate of 50 cc./kg./min., and oxygen flow rates of 3:1. Mean arterial pressure at the lower perfusion rate was 80 mm. Hg., while a rate of 70 cc./kg./min., resulted in pressures of at least 100 mm. Hg. The mixing column was 2.5 x 50 cm., and the defoamer 5 x 60 cm.

A second group of experiments was carried out in an identical manner but the perfusion period was extended to 2 hours in order to detect development of an oxygen debt. Satisfactory arterial oxygen saturation levels of 93 to 96% were again noted with perfusion rates of 50 and 70 cc./kg./min., with 3:1 and 2.2:1 oxygen flow rates respectively. With this longer perfusion, however, a progressively increasing A-V oxygen saturation difference was noted with the lower blood perfusion rate. This indicates that the amount of oxygen transported by the blood in this circumstance was insufficient to supply body requirements. A progressive oxygen debt developed. This observation was not made when a blood flow rate of 70 cc./kg./min., was used. When oxygen flow rates above 2.2:1 were used with a blood perfusion rate of 70 cc./kg./min., the arterial oxygen saturation reached the 98-100% range and the venous saturation exceeded 80%. The A-V oxygen saturation difference decreased progressively with time, indicating the utilization of dissolved plasma oxygen by the perfused animal.

These investigations demonstrate that there is a low optimal oxygen flow rate for the oxygenator which can be related to the body weight of the perfused subject. This oxygen flow rate is significantly lower than that commonly in use with the bubble oxygenator. This value was repeatedly determined to be between 150 and 180 cc. of oxygen/kg. of body weight of the perfused subject. Bubble size, and oxygenator length (which determines the length of time blood is exposed to oxygen at the liquid-gas interface) are factors which determine efficiency of the apparatus and must be standardized. As a check on these observations, cardiopulmonary by-pass was performed using a continuous oxygen flow rate of 150 cc./kg. body weight while the blood flow rate was increased to levels which maintained normal aortic pressures. As might be expected, perfusion rates in the latter range (70-80 cc./kg./min.) were productive of the most physiologic oxygenation (Table 2) in the arterial and venous blood. *A 30% increase in oxygen transportation occurs when blood flow is increased from 50 to 70 cc./kg./min.*

The pH of the blood was usually low during cannulization and steadily increased to normal values during the perfusion when the higher blood flows were used. Carbon dioxide tension levels remained in the physiologic range during use of the 2.2:1 oxygen flow rates. Plasma hemoglobin levels were below 100 mgm. and fibrinogen determinations within normal limits under these circumstances. Debubbling was simplified due to a lack of foaming with the low oxygen flow rates.

SUMMARY AND CONCLUSIONS

Short of an ideal perfusion technique which has as yet to appear, a reasonable goal would be a perfusion which resulted in physiologic values for the readily

Bl. Flow cc/Kg/min.	Bl. Flow Total	O_2 Flow Ratio	O_2 Flow Total	Temp. Rectal	Temp. Water bath	B. P. Art. mm. Hg.	B. P. Ven. Cm. H_2O	Art. O_2 Cont.	Art. Sat.	Ven. O_2 Cont.	Ven. Sat.	A-V diff.
50	650	2/1	1.3	94	108	80	-5	17.9	87	11.2	57	6.7
50	650	3/1	2.0	94	108	75	-6	19.4	86	11.7	59	7.7
50	650	4/1	2.5	93	110	95	-4.5	20.8	97	10.0	50	10.0
50	650	5/1	3.0	93.5	110	100	+3	23.1	99	12.9	61	10.2
50	650	6/1	3.9	93.5	108	120	+7	22.2	95	15.5	75	6.7
70	910	2/1	2.0	93	110	90	-4	19.7	88	13.7	66	6.0
70	910	3/1	2.5	93	112	100	-3	20.7	96	15.0	70	5.7
70	910	3.5/1	3.0	93	110	115	-3.5	21.7	94	15.1	72	6.6

Table II

Table 2

Perfusion data obtained by varying the blood flow rate while total oxygen flow remains constant.

measurable blood constituents. Normal and occasionally above normal blood flow rates will be required to meet the preoperative cardiac output of the perfused subject.

In an attempt to approach physiologic perfusion, abnormally high arterial oxygen tensions which might lead to gas embolism should be avoided. Satisfactory oxygen saturation levels unaccompanied by excessive oxygen partial pressures were obtained with surprisingly low oxygen flow rates (2.2:1) in the bubble oxygenator. These results were attained only when using blood flow rates of at least 70 cc./kg./min. Under these conditions, the arterial-venous oxygen saturation difference remained constant during long perfusion periods. The latter probably constitutes a critical test of oxygen transportation and utilization. The principles derived from these studies have been applied to clinical perfusions with very satisfactory results.

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