A Computer Monitored, Recirculating, Equilibrium Test Circuit for Artificial Blood Oxygenator Gas and Heat Transfer Characterization

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Abstract

An In Vitro test circuit that features continuous direct monitoring of blood gases, pH, temperature, hemoglobin O_2 saturation, blood flow, gas flow and pressure is presented. Previous test circuit designs and features are presented.

A microcomputer monitors the directly measured parameters, presents the investigator with test control variables and allows the user to collect gas and heat transfer data with a single key stroke. Control parameters and test results are presented immediately and stored in a data file for statistical analysis and graphic presentation.

The microcomputer is employed to present the technologist with AAMI Standard test condition parameters and variables that quantitate oxygenator "stress" to allow rapid control of the deoxygenator loop. The computer assisted ability to control test conditions facilitates testing, improves the statistical consistency of the data and minimizes time to collect, analyze and compare device data.

Employing the computer test circuit decreased study time for a single device characterization from 8 hours to 2–3 hours. Additionally, hemoglobin P_{50}, mixed venous blood conditions, the forcing function for O_2 and CO_2 transfer, the test oxygenator respiratory quotient and failure conditions are easily monitored, eliminating the recording of invalid data.

Introduction

The concept and methods of an In Vitro, recirculating equilibrium test circuit to evaluate artificial lung and extracorporeal heat exchanger function have been described numerous times.[4,6,7,8,10,12] This communication describes a test circuit that features computerized on-line data collection and recirculation.[1]

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In Vitro artificial lung testing circuits and protocols are burdened by long periods of conditioning the test blood to the proper oxygen and carbon dioxide content. Additionally, discrete sampling processes extend the time to completely analyze a single device to several hours.

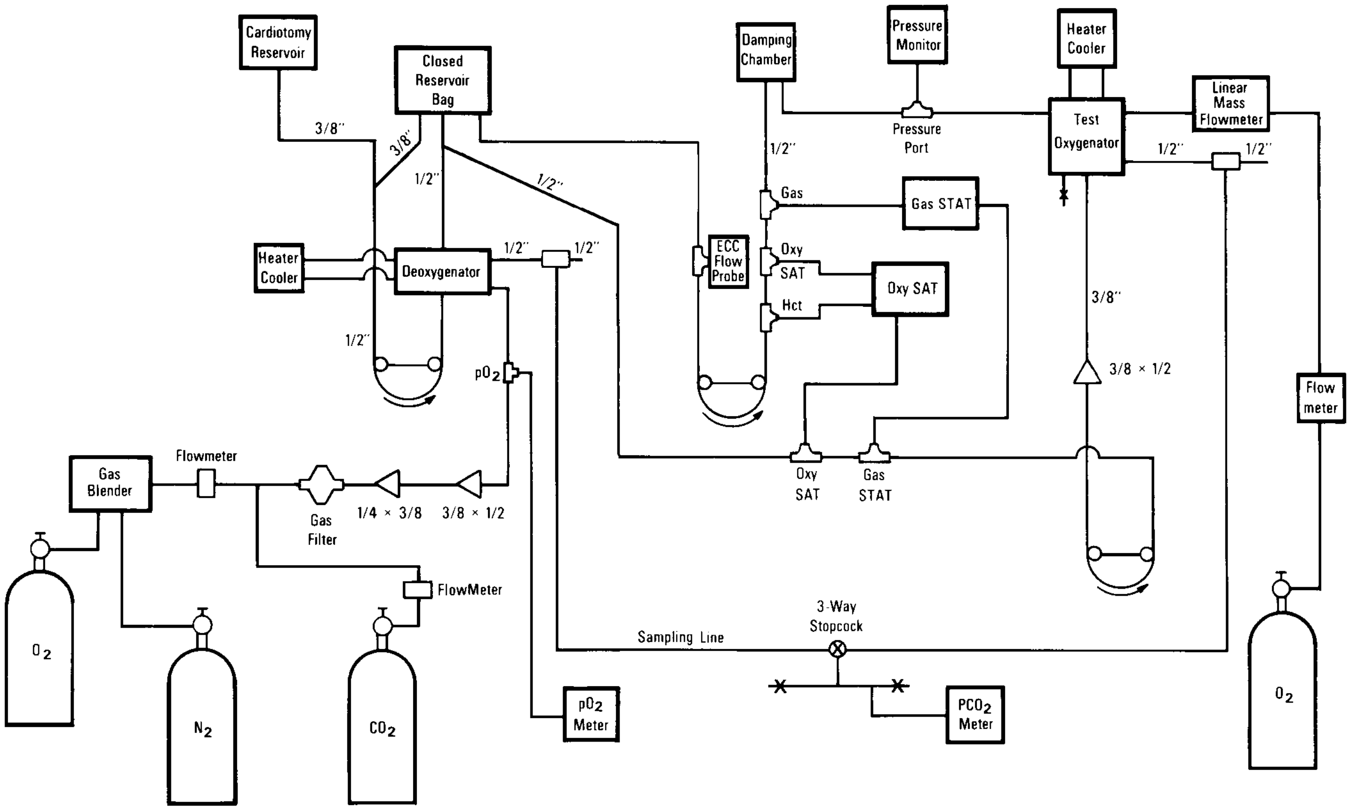
Artificial lung function curves created In Vitro must be clinically relevant and generate data useful to clinicians employing the device in early clinical trials. Typically the Association for the Advancement of Medical Instrumentation (AAMI) standard testing is performed In Vitro to "stress" the test oxygenator. The AAMI standard differs from typical clinical conditions in that the hematocrit is required to be 36 ± 2% and there is no minimal outlet pO_2 requirement; a saturation of 95% is to be achieved with the inlet saturation equal to 65%. There is no AAMI statement in regard to the test blood hemoglobin P_{50} except indirectly that the pH, pCO_2, BE and temperature must be within normal venous limits at a saturation of 65%. The test blood 2,3 DPG may be low and the test hemoglobin have an increased infinity for oxygen which will bias the test in favor of the oxygen.[2] Hemoglobin P_{50} should be evaluated during testing to assure normalcy. Oxygenator pO_2 function curves have smaller standard deviations when P_{50} is known, unchanging, or the data is adjusted to a normal P_{50}.

Hemoglobin saturation, hematocrit, pO_2, pCO_2, pH, temperature, gas phase pCO_2 and pO_2, blood flow, water flow, gas flow, and pressure may be monitored continuously and continuous analog signals provided for computer collection.[1] The computer monitor test circuit presented herein employs the computer and transducer measuring systems described in detail previously.[1]

Materials and Methods

Figure 1 presents the gas and heat transfer In Vitro test circuit and the necessary transducer/monitors to provide continuous computer surveillance.

Article available at https://ject.edpsciences.org or https://doi.org/10.1051/ject/1986182061



GAS AND HEAT TRANSFER TEST CIRCUIT

Figure 1: The In Vitro recirculating, equilibrium test circuit to quantitate gas and heat transfer in artificial lungs.

The circuit centers around the closed reservoir bag. Two large surface area hollow fiber membrane oxygenators serve as the deoxygenator and closed reservoir blood contents are recirculated through the deoxygenator at a blood flow about twice the value of the test oxygenator blood flow rate. The deoxygenator is ventilated with a mixture of O_2, N_2, and CO_2. The deoxygenator inlet pO_2 and pCO_2 are measured to facilitate the venous blood conditioning in the closed reservoir bag.

"Venous" blood is drawn from the closed reservoir bag, pumped through a damping chamber if the oxygenator is designed for pulse-less mixed venous return, so not to possibly change any sparger dynamics. Blood flow, hemoglobin O_2 saturation, temperature, blood gases, pH, and venous inlet pressure are measured before the test oxygenator in this segment of the circuit. Microbubble detection system probe may be introduced after a bubble trap to measure gaseous microemboli in this tubing segment.

The deoxygenator and the test oxygenator have separate high water flow sources to allow maintenance of the closed reservoir bag at a constant temperature to evaluate the test oxygenator integral heat exchanger.[7]

The test oxygenator outlet blood line contains continuous monitors of pressure, temperature, blood gases, pH, and hemoglobin O_2 saturation. If a bubble oxygenator with an open arterial reservoir is tested, the oxygenator outlet blood must be pumped to the closed reservoir bag. A membrane test oxygenator does not require an outlet pump.

The test oxygenator gas flow, inlet gas pO_2, and exhaled gas pCO_2 are continuously measured and they are varied in the test.[9,10]

Blood flow, gas flow, and FiO_2 to the test oxygenator are varied and the deoxygenator blood flow, gas flow, FiO_2, $FiCO_2$, and sweep rate are varied to condition the closed reservoir bag blood O_2 and CO_2 content to meet AAMI or clinical venous inlet blood conditions. The values from the continuous monitors are updated on the computer screen every twelve seconds. A single keystroke creates the printout found in Printout 1.

Printout 1 provides a hard copy to document the oxygenator test inlet conditions and resulting perfor-

TEST OXYGENATOR / HEAT EXCHANGER :MAXIMA
TEST OXYGENATOR / HEAT EXCHANGER SERIAL NUMBER 7306
STUDY TEST HEMATOCRIT = 28 %

H E A T E X C H A N G E R E V A L U A T O R

SAMP NO.	H2O OC	VEN OC	ART OC	TWI-TBI	OPEN OX COL	BLD L/M	GAS L/M	GBQR UNIT	CHE UNIT	KCAL/ MIN
1	37.9	22.4	31	15.5	0	1	.5	.5	.55	8.03
2	37.8	22.3	35.1	15.5	0	1.5	.75	.5	.83	17.94
3	37.3	23.3	35.5	14	0	2	1	.5	.87	22.79
4	37.4	24.1	35.1	13.3	0	2.5	1.25	.5	.83	25.69
5	37.3	24.9	34.6	12.4	0	3	1.5	.5	.78	27.18
6	37.6	24.7	35	12.9	0	3	1.5	.5	.8	28.87
7	37.4	25.2	34.4	12.2	0	3.5	1.75	.5	.75	30.08
8	37.6	25.2	34.5	12.4	0	3.5	1.75	.5	.75	30.41
9	37.5	25.3	34.3	12.2	0	4	2	.5	.74	33.63
10	37.4	25.3	34.2	12.1	0	4	2	.5	.74	33.26
11	37.5	25.5	34	12	0	4.5	2.25	.5	.71	35.73
12	37.1	25.5	33.7	11.6	0	4.5	2.25	.5	.71	34.47
13	37	25.8	33.3	11.2	0	5	2.5	.5	.67	35.03
14	36.9	25.7	33.2	11.2	0	5	2.5	.5	.67	35.03
15	36.3	25.9	32.5	10.4	0	5.5	2.75	.5	.63	33.91
16	36.3	25.6	32.7	10.7	0	5.5	2.75	.5	.66	36.48
17	35.8	25.5	32.1	10.3	0	6	3	.5	.64	36.99
18	35.7	25.4	31.9	10.3	0	6	3	.5	.63	36.43
19	35.1	25.5	31.3	9.6	0	6.5	3.25	.5	.6	35.22
20	34.9	25.4	31.1	9.5	0	6	3	.5	.6	31.95
21	34.3	25.3	30.5	9	0	7	3.5	.5	.58	34
22	34.1	25.2	30.3	8.9	0	7	3.5	.5	.57	33.35

Printout 1: The on-line printout of the heat exchanger performance factor or coefficient of heat exchange (CHE) and heat flow in kilocalories per minute.

mance variables. It is the user's responsibility to assure that the circuit is in equilibrium (inlet and outlet continuously measured parameters are unchanging). Printout 1 represents values from a Maxima[a] test oxygenator.

The "LMPCO2" and "VCO2" are after the work of Snider, et al.[10] The "P50," "SVO2," "GBQR," "AVO2," and "VO2" are employed to evaluate the test oxygenator oxygen transfer ability. The "user code" in Printout 1 is the Maxima gas inlet pO_2 for use in manipulations described by Curtis and Eberhart.[9]

Printout 2 is the output of the software written to evaluate the Maxima heat exchanger. The formula for the performance factor or coefficient of heat exchange and the heat flow in kilocalories per minute have been described previously.[7]

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The Monitor software creates a disk file of variables that may be passed to a data base/statistics package. Any variable pairs may be sorted and passed to a least-squares regression algorithm to obtain a best-fit equation and standard deviation of fit.

Data files from the tests of three Maxima hollow fiber membranes were joined and the appropriate data pairs analyzed to create linear or logrithmic regression equations and standard deviations of fit.

Results

Figures 2 and 3 present the mean performance of the test Maximas in regard to pressure drop and heat transfer ability.

Figure 4 presents the Maxima pO_2 versus gas path FiO_2 or pO_2 isobars. The inlet venous blood percent saturation of hemoglobin with oxygen was held at 60% ± 2.2% (1 S.D.) and the hematocrit was 28% ± .7%

Date: Mar. 22, 1986 Disk Filename: MAXIMA Run # 1

CLOCK TIME	SAMP #	ELAP MIN	SAO2 %	BLD L/M	GAS L/M	FIO2 %	FICO2 %	LMPCO2 MMHG
14:51	46	271	92.9	6	9	100	0	9.4

BLD oC	HCT %	HGB GM%	LINE mmHg	PEXCO2 mmHg	PO2 mmHg	PCO2 mmHg	PH UNIT	B.E. MEQ/L
36.2	28	9.8	4	19	103	30.5	7.54	.8

SVO2 %	P50 mmHg	GBQR UNIT	AVO2 VOL%	VO2 ML/M	VCO2 ML/M	R.Q. UNIT	USER CODE
62.2	19.3	1.5	4.03	241.8	241.9	1	399

Date: Mar. 22, 1986 Disk Filename: MAXIMA Run # 1

CLOCK TIME	SAMP #	ELAP MIN	SAO2 %	BLD L/M	GAS L/M	FIO2 %	FICO2 %	LMPCO2 MMHG
14:53	47	274	89.9	6	6	100	0	11

BLD oC	HCT %	HGB GM%	LINE mmHg	PEXCO2 mmHg	PO2 mmHg	PCO2 mmHg	PH UNIT	B.E. MEQ/L
36.2	28	9.8	3	27	106	33	7.52	1.3

SVO2 %	P50 mmHg	GBQR UNIT	AVO2 VOL%	VO2 ML/M	VCO2 ML/M	R.Q. UNIT	USER CODE
59	20.9	1	4.06	243.6	229.2	.94	401

Date: Mar. 22, 1986 Disk Filename: MAXIMA Run # 1

CLOCK TIME	SAMP #	ELAP MIN	SAO2 %	BLD L/M	GAS L/M	FIO2 %	FICO2 %	LMPCO2 MMHG
14:54	48	275	90.4	6	6	100	0	10.3

BLD oC	HCT %	HGB GM%	LINE mmHg	PEXCO2 mmHg	PO2 mmHg	PCO2 mmHg	PH UNIT	B.E. MEQ/L
36.2	28	9.8	3	24	102	33	7.51	.6

SVO2 %	P50 mmHg	GBQR UNIT	AVO2 VOL%	VO2 ML/M	VCO2 ML/M	R.Q. UNIT	USER CODE
59	20.9	1	4.12	247.2	203.7	.82	400

Printout 2: Printer listing of test circuit control parameters at the time that control and measured transfer parameters are saved for further analysis. User code is the Maxima gas path pO_2 in mmHg. $LMPCO_2$ is the log mean delta pCO_2. $PEXCO_2$ is the Maxima expired gas pCO_2.

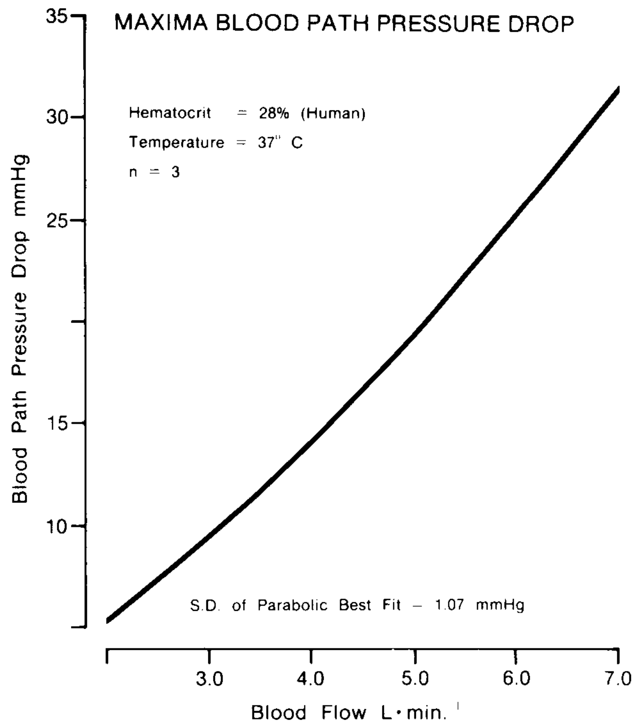

Figure 2: Maxima blood path pressure drop versus blood flow.

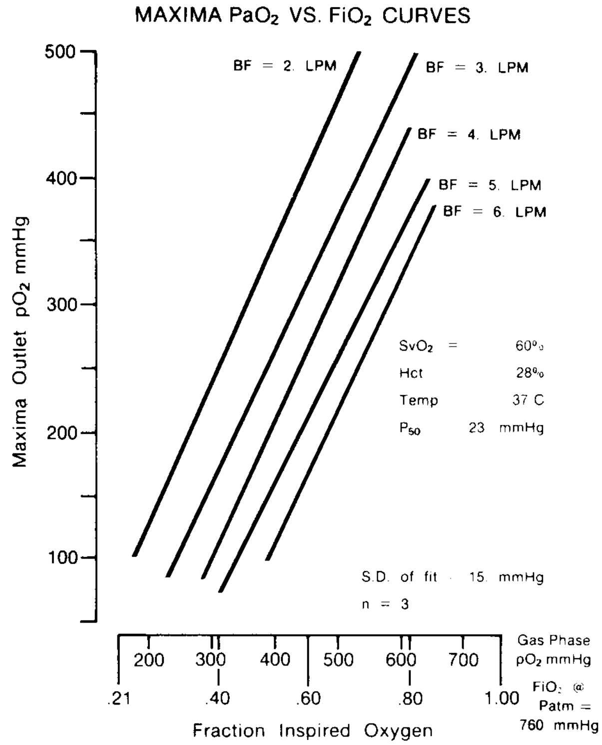

Figure 4: Maxima outlet pO_2 versus FiO_2 function curves for various blood flow rates holding mixed venous inlet oxygen content constant.

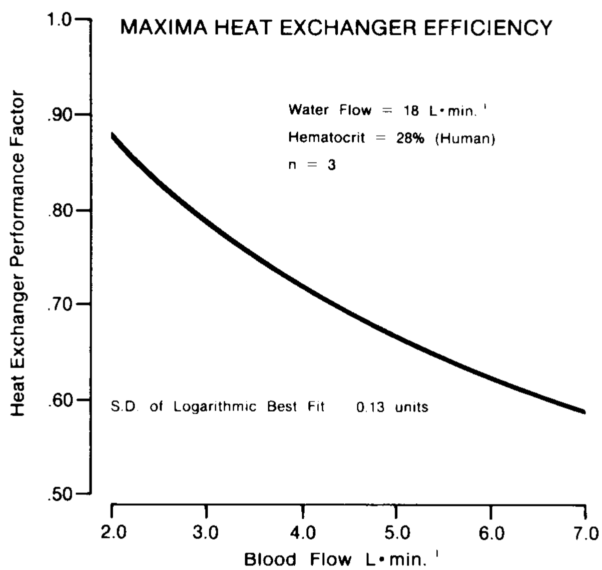

Figure 3: Maxima heat exchanger efficiency versus blood flow rate.

for the three tests that include multiple samples for oxygenation. Lower Maxima blood flows (greater blood residence time) require less FiO_2 to achieve the same outlet blood pO_2.

Figure 5 presents the effect of varying mixed venous saturation on the Maxima outlet pO_2 and gas transfer ability (VO_2 and VCO_2) at two FiO_2 settings. The outlet pO_2 did not fall below 100 mmHg at an FiO_2 equal to .40 until the mixed venous saturation fell below 66%. It appears that the Maxima could oxygenate (pO_2 greater than 100 mmHg) a mixed venous saturation equal to 20% at an FiO_2 equal to .80.

Figure 6 presents the CO_2 transfer curves for the Maxima versus the forcing function for CO_2 transfer, the log mean delta pCO_2.[10] The Maxima CO_2 transfer normalized to the blood flow was very consistent across the range of blood flows tested (2–6 liters per minute). Increasing the Maxima GBQR above 1.25:1.0 does not substantially increase VCO_2. By all previously reported standards, the Maxima function curves for pressure drop, heat and gas transfer are exceptional, controllable, and reproducible.[4-12]

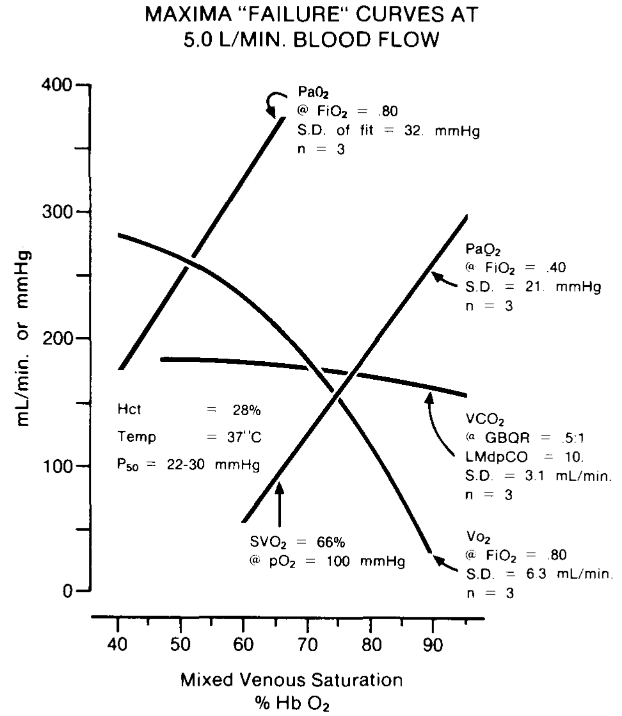

Figure 5: The effect of varying mixed venous O_2 saturation of hemoglobin on oxygen transfer, carbon dioxide transfer and Maxima outlet pO_2 at FiO_2s of .8 and .4. Note the Haldane effect.

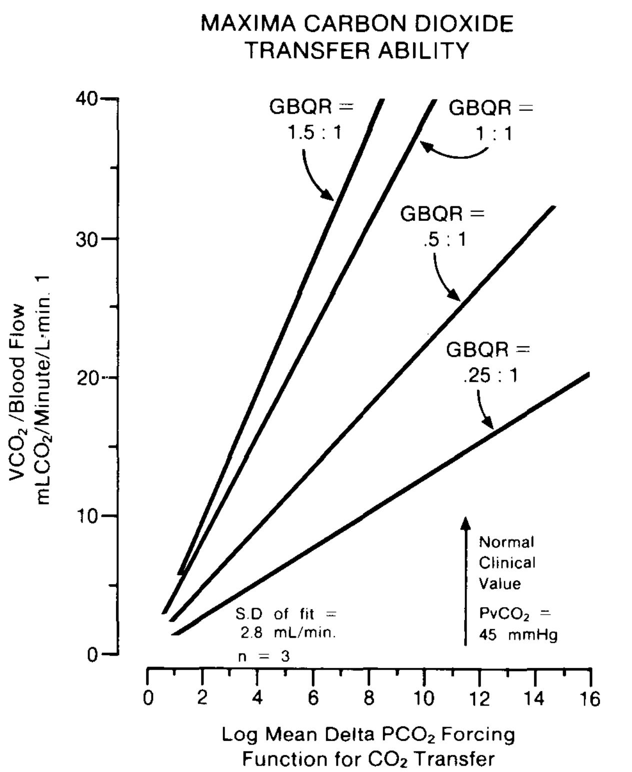

Figure 6: The effect of varying the $LMdPCO^2$ ($PvCO_2$) on CO_2 transfer per L/min of Maxima blood flow at various GBQRs. Increasing GBQR above 1.25:1.0 is apparently rate limited.

Discussion

Use of the computer monitored, recirculating equilibrium test circuit has facilitated a time-consuming process that typically consumed 8 to 12 hours to collect data and a similar time to reduce the data. Use of this method has reduced the complete data collection process to two hours and the data analysis process to less than two hours.

The immediate user availability of the data in Printout 1 and the control values on the computer screen expedite the circuit balancing and sampling processes and, most importantly, improve the accuracy of multiple sampling and decrease the chance of recording invalid sample data points.

Many test oxygenators and many clinical and AAMI standard conditions may be tested in a short period of time. Clinically relevant data (e.g. pO_2 isobars, Figures 4 and 5) are easily obtained and the reproducibility of the oxygenator quantitated as the circuit controlled parameters' deviations are minimized.

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Question from the Audience

Question—(Unknown): Is it difficult to make calculations when you have different response times in what are you doing?

Answer: One thing that has to be done with the circuit is to study the dynamics and the response time with the devices. If you make a change in the control parameters of the oxygenator it takes a while for the blood and the oxygenator to equilibrate and then the Gas-STAT, the Oxy-Sat and the other analyzers to come to equilibrium with the blood. When we make a change it usually takes 8 to 12 minutes for the circuit to re-equilibrate and for the parameters not to be changing before we can take another data set. It's an excellent point.