The pO_2 of Samples Drawn from the Shiley S-100A Arterial Reservoir Is Not an Accurate Indicator of Arterial Line pO_2

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Abstract

While conducting clinical bypass with the Shiley S-100A bubble oxygenator, an observation was made that arterial pO_2 values reported by the laboratory were routinely inconsistent with inline arterial blood oxygen saturation measurements. It was also noted that the blood in the arterial reservoir in the vicinity of the arterial sampling port was often darker in color than the blood in the arterial line.

Sixty-four simultaneously drawn pairs of arterial blood gas samples were drawn from the arterial reservoir sampling port and from the purge line of the arterial line filter (ALF). In all instances, the pO_2 of the sample drawn from the arterial line filter exceeded the pO_2 of the corresponding sample drawn from the arterial reservoir. The percentage difference between the pO_2 of samples drawn from the ALF and from the arterial reservoir correlated strongly ($p < .01$) with the arterial blood temperature and moderately ($p < 0.2$) with the reservoir level. No significant differences were found between the pCO_2, pH and base excess of the ALF and the arterial reservoir.

The authors postulate that the discrepancy in pO_2 between the arterial reservoir sampling port and the ALF is a result of rapid channelling of partially oxygenated blood through the defoamer into the vicinity of the arterial sampling port. The rapidly channelled blood is, therefore, deprived of the additional oxygenation that occurs in the defoamers of bubble oxygenators.

It is recommended that Shiley reposition the S-100A's arterial sampling port closer to the arterial reservoir outlet port and that a unidirectional valve be inserted to prevent inadvertent introduction of air to the arterial reservoir. Until this design modification is carried out, the authors recommend that clinical users of the S-100A draw arterial blood gas samples directly from the arterial line or from the ALF purge line.

Introduction

While conducting clinical bypass with the Shiley-S-100A bubble oxygenator, it was noticed that arterial pO_2 values reported by the laboratory were routinely inconsistent with inline arterial blood oxygen saturation indications. It was also observed on frequent occasions that the blood in the arterial reservoir in the vicinity of the arterial sampling port was visibly darker in color than the blood in the arterial line. A concern arose that adjustments in perfusion management that were based on indicated arterial reservoir pO_2s were being made that were inconsistent with and perhaps detrimental to the patient's actual requirements. This investigation was undertaken to verify and quantify the existence of a discrepancy between blood gas samples taken from the arterial sampling port and blood actually delivered to the patient.

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Materials and Methods

Sixty-four simultaneously drawn pairs of arterial blood gas samples were drawn from the arterial sampling port of the Shiley[a] S-100A bubble oxygenator and from the purge line of the American Bentley[b] AF-1025 arterial line filter (ALF) during 21 clinical coronary artery bypass procedures. In addition, 23 pairs of arterial blood gases were drawn from the same site throughout the study to establish the reproducibility of the blood gas analyzers' results. The 6 ml. sample lines through which the arterial reservoir samples were drawn were routinely purged with 30 ml. of blood from the reservoir prior to withdrawing the 3 ml. arterial blood gas sample. The side port of the continuously purged stopcock through which the ALF blood gas samples were drawn was routinely purged with 10 ml. of blood prior to drawing the 3 ml. sample. In both instances, the purge blood was returned to the venous side of the oxygenator. All blood samples were carefully purged of bubbles and tightly capped prior to being sent on ice to the laboratory.

The blood samples were analyzed with either a Corning[c] Model 178 or an Instrumentation Laboratories[d] Model 813 blood gas analyzer. In all instances both blood samples of each pair were analyzed by the same instrument. All blood gas results were reported and recorded at 37 °C.

The cardiopulmonary bypass circuit consisted of a Sarns[e] 5000 or 7400 roller pump, a Shiley[a] S-100A bubble oxygenator, an American Bentley[b] AF-1025 arterial line filter with undirectional purge line and an additional stopcock and purge line in series for sampling, an American Bentley[b] BCR-3500 cardiotomy reservoir, an American Bentley[b] PF-302 gas filter and American Bentley[b] PVC tubing.

Hypothermia (26-28 ° C) was induced in all cases. Blood gas samples were drawn at various stages of hypothermia as well as at 37 °C. Anticoagulation was maintained at an activated clotting time of at least 480 seconds as determined by the celite activated Hemochron[f] system and a concentration of 350 units heparin/kg body weight as measured by the HemoTec[g] Hepcon system—Model A-10 C & D. All patients were oxygenated with 100 percent O_2. Arterial saturation was monitored by an American Bentley[b] Oxy-Sat and maintained at 99-100 percent. Attempts were made to maintain blood flow at a rate high enough to sustain a venous O_2 saturation greater than or equal to 70 percent.

The raw data collected for this study consisted of the pO_2, pCO_2, pH and base excess of samples taken from the ALF and from the arterial reservoir, the volume of blood in the arterial reservoir at the time of sampling, the arterial blood temperature, blood flow, gas flow and the arterial and venous saturations. The data was analyzed by the Student-t test and by multiple linear regression with the aid of Micro-STAT[h], a statistical analysis computer program.

Results

In all instances, the pO_2 of the samples drawn from the ALF exceeded the pO_2 of the samples drawn from the arterial reservoir (Table 1). The mean difference between the ALF pO_2 and the reservoir pO_2 was 56 mm. Hg with a peak difference of 111 mm. Hg. These figures represent a mean percentage difference of 24 percent with a peak percentage difference of 87 percent. The standard deviation in pO_2 of the blood gas analyzers used for this study was ± 8 mm. Hg (± 3 %) when 23 pairs of control samples drawn from the same site were analyzed (Table 2).

The percent difference between the pO_2 of samples drawn from the ALF and from the arterial reservoir (d% pO_2) correlated strongly ($p < .01$) with the arterial blood temperature (ABT) and moderately ($p < 0.2$) with the reservoir level (RL). The following equation expresses this relationship.

$$d\%\ pO_2 = (ABT) \times (1.721) + (RL) \times (.0068) - 38.40$$

The coefficients in the above equation were derived by a statistical computer program utilizing multiple linear regression. Each coefficient reflects the level of significance of its respective variable and takes into consideration the cross-referenced correlations between independent variables.

No statistically significant discrepancies were found between the pCO_2, pH or base excess of samples drawn from the arterial reservoir and the ALF purge line.

The general trend of these results were verified in an independent informal study conducted at Harper Hospital in Detroit, Michigan (personal communication: Perfusion Department, Harper Hospital, Detroit, MI 48201).

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b American Bentley Laboratories, Irvine, CA, 92714
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f International Technidyne, Inc., Metuchen, NJ 08840
g HemoTec, Inc., Inglewood, CO 80112
h Ecosoft, Inc., Indianapolis, IN 46268

Table 1
S-100A Data

Res. pO_2 (mmHg)	ALF. pO_2 (mmHg)	Res. Lev. (ml)	ABT (°C)	BQ LPM	SVO_2 (%)	Delta pO_2 (mmHg)	Delta% (%)
280	325	600	24	4.0	88	45	16.07
198	264	900	26	3.4	81	66	33.33
89	167	700	37	4.6	68	78	87.64
196	259	1700	32	4.3	m	63	32.14
386	458	2200	26	3.3	m	72	18.65
405	420	1800	26	3.3	m	15	3.70
224	306	1400	38	4.7	59	82	36.61
102	113	600	30	4.7	65	11	10.78
245	284	600	30	3.5	73	39	15.92
159	193	700	38	4.2	70	34	21.38
478	495	2000	23	4.4	57	17	3.56
385	407	2000	26	3.2	m	22	5.71
326	341	1600	37	5.0	m	15	4.60
352	374	1000	28	3.6	m	22	6.25
324	399	700	37	3.8	90	75	23.13
315	359	2000	26	3.4	79	44	13.97
432	478	1600	26	3.5	84	46	10.65
232	271	1200	37	4.6	87	39	16.81
360	376	m	37	3.6	89	16	4.44
175	268	2000	26	4.0	69	93	53.14
264	369	1200	26	4.0	80	105	39.77
108	245	m	37	4.3	81	137	126.85
329	381	1200	27	3.5	85	52	15.81
248	335	1400	26	3.5	72	87	35.08
352	417	1200	26	3.7	76	65	18.47
272	320	1000	37	4.5	77	48	17.64
396	446	600	24	3.5	76	50	12.63
351	428	1000	25	3.0	52	87	29.94
191	261	600	37	4.6	89	70	36.65
181	229	1900	27	4.0	86	48	26.52
270	311	1300	27	4.0	68	41	15.19
189	203	900	37	4.9	82	14	7.41
353	393	1000	27	4.0	86	40	11.33
292	358	800	33	3.7	77	66	22.60
215	290	1000	37	4.0	89	75	34.88

Table 1 lists the pO_2 of samples drawn from the integrated arterial reservoir sampling port (Res. pO_2), of the pO_2 of samples drawn from the purge line of the arterial filter (ALF pO_2), the pO_2 difference between the two samples (delta pO_2) and the percentage difference between the two samples (delta % pO_2). Table 1 also includes the reservoir level (Res. Lev.), the arterial blood temperature (ABT), the blood flow (BQ), and the venous, O_2 saturation (SvO_2) at the time of sampling. The letter "m" denotes missing data.

Table continues next page

Table 1 (continued)
S-100A Data

Res. pO_2 (mmHg)	ALF. pO_2 (mmHg)	Res. Lev. (ml)	ABT (°C)	BQ LPM	SVO_2 (%)	Delta pO_2 (mmHg)	Delta% (%)
378	391	1100	27	2.5	86	13	3.44
386	461	800	37	3.5	84	75	19.43
92	123	2200	27	2.9	81	31	33.70
228	284	2100	26	3.5	81	56	24.56
163	231	900	37	4.3	77	68	41.71
398	428	1000	27	4.4	84	30	7.54
389	439	1900	26	3.4	75	50	12.85
308	362	1400	36	4.8	89	54	17.53
310	359	1900	26	4.2	86	49	15.81
303	340	1500	26	3.1	81	37	12.21
172	273	800	37	4.3	80	101	58.78
290	338	1300	27	4.5	86	48	16.55
219	291	1600	26	3.7	82	72	32.88
93	158	1600	37	4.5	69	60	61.22
95	145	2000	37	4.2	72	50	52.63
339	385	1000	34	4.2	80	46	13.57
97	179	2000	37	4.7	64	80	84.54
320	369	800	37	4.7	65	49	15.31
435	508	1600	26	3.8	88	73	16.78
456	555	1500	26	3.8	88	99	21.71
348	436	1400	26	3.8	90	88	25.29
337	448	2000	37	5.0	79	111	32.94
300	357	1400	28	4.0	86	57	19.00
343	432	1200	28	3.5	81	89	25.95
439	509	1000	27	3.4	80	70	15.95
225	292	1500	26	4.3	75	67	29.78
228	288	m	28	3.7	76	60	26.32
155	249	800	37	4.3	72	94	60.65
291	320	1300	27	4.7	87	29	9.97

Table 2
Blood Gas Analyzer Control Data

Sample One (mmHg)	Sample Two (mmHg)	Res. Lev. (ml)	ABT (°C)	BQ (LPM)	SvO_2 (%)	Delta pO_2 (mmhg)	Delta % pO_2 (%)
306	314	1000	28	4.3	86	8	2.16
305	299	1300	27	4.3	86	-6	-1.96
205	211	1300	37	5.0	77	6	2.93
171	172	800	37	5.0	68	1	2.93
268	265	1100	27	4.1	83	-3	-1.12
276	276	1100	27	4.2	84	0	0.00
124	111	1300	37	4.5	74	-13	-10.48
417	423	1400	25	3.3	88	6	1.44
424	426	1400	26	3.0	78	2	0.47
230	223	1200	36	3.8	66	-7	-3.04
453	451	1000	26	4.4	91	-2	-0.44
560	556	800	26	3.7	88	-4	-0.71
344	345	800	37	5.4	72	1	0.29
329	328	1200	24	3.1	86	-1	0.30
322	323	1200	27	3.1	80	1	0.31
436	436	1200	27	3.1	82	0	0.00
314	302	1400	38	3.7	73	-12	-3.82
346	345	1800	26	4.0	85	1	+0.29
461	482	1200	28	4.0	71	21	4.55
355	353	1300	37	4.3	90	-2	-0.56
352	345	2100	27	4.4	74	-7	-1.98
321	335	m	27	4.1	87	14	4.36
229	236	m	37	4.6	86	7	3.06

Table 2 lists the pO_2 of two arterial samples drawn immediately sequentially from the same sampling site (Sample One and Two), the pO_2 difference between the two samples (delta pO_2) and the percentage difference between the two samples (delta % pO_2). Table 2 also includes the reservoir level (Res. Lev.), the arterial blood temperature (ABT), the blood flow (BQ) and the venous O_2 saturation at the time of sampling (SvO_2). The letter "m" denotes missing data.

Discussion

Discrepancies between pO_2 values of samples drawn from arterial reservoirs of oxygenators and from the arterial line have been reported in previous studies. Hansen et al. (1981) reported significant discrepancies (-60.4% to +42.2%) between the pO_2 of samples drawn from both of the Polystan oxygenators-Models VT2000 and VT5000 when compared to samples drawn from the arterial line.[1] Gravenstein et al. (1985) reported consistent discrepancies between both the pO_2 and the pCO_2 of samples taken from the Harvey H-1700 arterial sampling port when compared to an arterial line sampling site.[2] The pO_2 was significantly overindicated (242 ± 78 mm Hg) from the reservoir versus 198 ± 79 mm Hg from the arterial line, $p < 0.001$) while the pCO_2 was significantly underindicated (44 ± 4 mm Hg from the reservoir versus 46 ± 5 mm Hg from the arterial line). Both Gravenstein et al. and Hansen et al. found no significant difference in pO_2 between samples taken from the arterial inflow line and from the aorta. It was upon this data that the authors of this present study based their assumption that blood drawn from the ALF purge line is representative of the arterial blood delivered to the patient. Pastoriza-Pinol et al. (1984) reported that arterial samples taken from the arterial sampling ports of five different bubble oxygenators were consistently poor indicators of radial artery pO_2.[3] Their pooled data indicated that, in general, bubble oxygenators tended to over estimate radial

artery pO_2 and that the ALF purge line offered a more reliable sampling site. Pastoriza-Pinol et al. also reported color differences in the blood in the arterial reservoir near the arterial sampling ports, as the authors of this study have also observed. The results of the Pastoriza-Pinol data were not reported for each oxygenator model but was presented only as pooled data.

It was not necessary to temperature correct the blood gas values since d% pO_2 is independent of the temperature at which blood gas results are reported.[4,5] The possibility that the discrepancy in pO_2 between the arterial reservoir sampling port and the ALF purge line was characteristic only of oxygenators from a single lot number was eliminated by including oxygenators from two lots. No apparent difference between lots was detected.

The most striking finding of this study was the dramatically consistent demonstration of the pO_2 discrepancy. In no instance did an individual pO_2 of a sample drawn through an arterial reservoir sampling port exceed or fall within one standard deviation of the pO_2 of the corresponding sample drawn from the ALF purge line. This consistency strongly suggests that some predictable characteristic of the S-100A's flow dynamics is responsible for the pO_2 variance.

The authors postulate that the observed differences in pO_2 between the sampling sites may be a result of rapid channelling of incompletely oxygenated blood through the defoamer into the vicinity of the arterial sampling port. The portion of blood which is channelled more rapidly through the defoamer than the majority of the blood volume would be deprived of the additional oxygenation generally assumed to occur in the defoamers of bubble oxygenators.[6]

The results of this study significantly link increases in d% pO_2 to increases in the arterial reservoir level and the arterial blood temperature. As the reservoir level increases, the residence time of unchannelled blood inside the defoamer increases as well, which allows the major portion of the blood to continue to oxygenate for a longer duration than that blood which is believed to have been channelled more rapidly through the defoamer into the vicinity of the arterial sampling port.[7]

The proposed effect of temperature is believed to be a result of well documented temperature dependent changes in oxygen solubility.[4,5,8] As colder blood enters the oxygenating column, its greater affinity for oxygen would result in a greater percentage of the potential oxygenation taking place in the oxygenating column, leaving only minimal oxygenation to be completed in the defoamer. This would result in smaller d% pO_2 variations between blood that remains in the defoamer for a longer period of time than blood which is believed to have been rapidly channelled out of the defoamer, thereby being deprived of additional oxygenation time. Warmer blood, having a much lower affinity for O_2, may complete a smaller proportion of its total potential oxygen adsorption in the oxygenating column. This would result in the channelled blood having much lower pO_2s than the major portion of the blood which transverses more of the entire length of the defoaming column, thereby maximizing its residence time in an environment more conducive to oxygenation than the arterial reservoir. It was interesting to note that there was not an inverse relationship between the venous saturation (SVO_2) and d% pO_2, as might have been expected. The authors suspect that this may have been a result of the relatively small volume of blood involved in the channelling phenomenon.

The possibility that the low pO_2s from the reservoir were a result of drawing samples from actual pockets of static blood was not supported by the pCO_2, pH or base excess data.

Conclusion

The discrepancies in pO_2 measurements between the arterial reservoir sampling port of the Shiley S-100A and the arterial filter purge line is probably the result of malposition of the arterial sampling port and defoamer channelling. It is believed that the sampling port is located in a position that encourages sampling primarily from blood channelled rapidly through the defoamer rather than from well mixed arterial blood which is more representative of the blood pumped to the patient. It is suggested that Shiley reposition the sampling site closer to the arterial port and that a undirectional valve be inserted to prevent inadvertent introduction of air to the arterial reservoir. Until this design modification is carried out, the authors recommend that clinical users of the S-100A draw arterial samples directly from the arterial line or from some other reliable site rather than from the arterial reservoir sampling site.

Finally, the authors wish to clearly state that the results of this study in no way effect their confidence in the Shiley S-100A's ability to consistently and safely oxygenate blood. The S-100A remains our bubble oxygenator of choice, although we no longer make use of the integrated arterial sampling port. In addition, it is

suspected that inconsistencies between blood drawn from integrated arterial sampling ports and blood actually delivered to the patient may be a problem common to many brands of oxygenators currently available. We strongly urge perfusionists who are currently using any oxygenator's integrated arterial sampling port to test the accuracy of samples drawn from that port and to make corrections in sampling sites if indicated.

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