A Technique For Highly Oxygenated Crystalloid Cardioplegia Delivery

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Abstract

(J. Extra-Corpor. Technol. 20[1]: p. 35-39 Spring 1988) **Development of a new cardioplegic solution (oxygenated crystalloid) and method of delivery is discussed from *in vivo* and *in vitro* testing and clinical use in over 4000 clinical cases. Assemblage of existing components into a new and safe device is presented.**

Introduction

Since the onset of cold potassium cardioplegia as a standard practice, a myriad of refinements to this technique has taken place over the last few years. Originally, temperature of the potassium solutions was the controversial topic; however, this debate finally subsided at our center and acceptable ranges were settled on from 4-8 °C.[1] The subject of temperature brought with it the question of which technique for cooling the solution was best: coil (polyvinyl chloride or metal), heat exchanger, or other methods.

Another area of concern was the method of delivery. At our institutions, the initial method of choice (no longer used), was the syringe technique, administered via a 60 ml syringe into the aortic root by the surgeon. We, as well as the surgeons, felt that this system had its inherent faults, such as the possibility of air or particulate emboli.[2]

After modifying a Pall transfusion filter[a] to filter out gross microemboli, the problem of air emboli as introduced via the syringe technique was still a possibility. Eventually, we moved to a recirculating system using a double roller pump, pumping through an ice bath via a PVC coil. We were concerned, however, with the problem of massive air embolism being introduced by the perfusionist. We tried to limit this possibility by using collapsible bags (with all air evacuated) and a bubble trap (which offers minimal safety at best).

After using several systems we determined three basic requirements for our system:

1. Due to the low temperatures of the solution (3-7 °C), a silastic tubing was thought necessary to achieve relatively high flow (200-400 ml/min) and high pressure (aortic root pressure of 80-95 torr). One quarter inch PVC tubing became stiff and collapsed at these temperatures and flows. However, some air emboli filters[b] cracked due to particulate matter thought to be from silastic tubing (Personal communication from American Bentley). We have since employed Bentley Bypass 65 class VI 1/16″ x 1/4″ polyvinyl chloride tubing[b] with no filter leaks and still maintain adequate flows.

2. There was a marked difference (1-4 °C) in efficiencies of cooling coils used. This was determined to be caused by surface area and heat exchange capabilities of PVC vs. aluminum or stainless steel. We settled on an aluminum coil (not compatible with blood). Ice baths also presented great variabilities in temperatures. The "magnetic stirrer"[b] concept proved to be the most efficient. (Graph 1)

3. A dual purpose filter (particulate and emboli) which had low priming volume and was easy to

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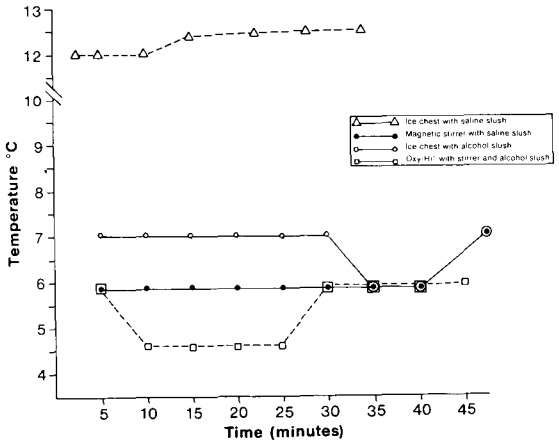
a Pall Biomedical Products Corp., East Hills, NY 11548
b American Bentley, Co., Irvine, CA 92714



Graph 1: Rate of Cooling of Cardioplegia Solution

debubble was desired. The Bentley .45 micron microbubble trap filter[b], filters the solution of potentially hazardous debris[3] as well as preventing gross air from reaching the patient.

Development

It was at this time (February 1983), that research was undertaken to determine the feasibility of the use of highly-oxygenated crystalloid cardioplegia.[4] Other solutions and adjuncts were considered such as: blood,[5] Fluosol,[6] and Nifedipine.[7] However, the crystalloid solution seemed to be the easiest and safest to adapt to our clinical situation. We then designed the elements of a system that could achieve pO_2 of 600 torr., a temperature of at least 5 °C and a safe filtered solution, free of microemboli which would also ensure against massive air embolism.

The elements needed in our system were: an unfiltered cardiotomy reservoir,[b] a bacteriostatic gas line filter,[b] an aluminum cooling coil,[b] PVC tubing,[b] with microbubble trap-filter,[b] and an O_2 flowmeter. The system designed proved to be safe, easy to set up, and prime.

Subsequent to this, a larger capacity unfiltered cardiotomy reservoir, the American Bentley BCR-3000[b] was employed in over 600 open heart cases (Figure 1). Since this was a prototype system American Bentley has modified its Q-120[b] reservoir so the oxygen inlet is positioned at the bottom of the reservoir rather than at the top (Figure 2), providing for two improvements over the first two prototypes. One improvement allows oxygenation of the entire volume in the reservoir, and not merely the portion recirculating through the top

b American Bentley, Co., Irvine, CA 92714

Prototype
Figure 1.

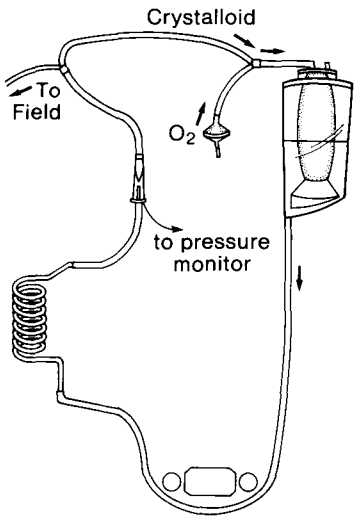


Figure 1: Initial model crystalloid cardioplegia set

OxyHi™
Figure 2.

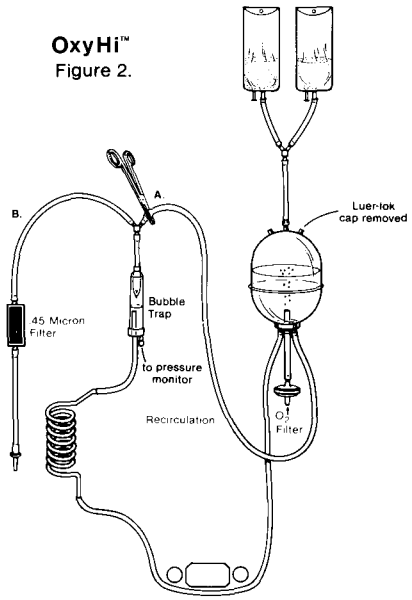
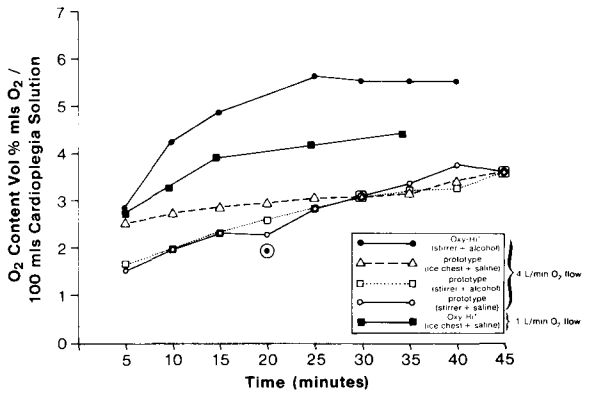


Figure 2: OxyHi.© Present oxygenated crystalloid system for Emory University Hospitals (Non-pressurized system)

area. The earlier system had a problem in that if additional solution had to be added to the system rapidly, it was impossible to oxygenate quickly. In addition, in the early prototypes, care was taken to ensure the bacteriostatic gas filter did not become wet. This is still a consideration in the Oxy-Hi[b] system and gas flow should be maintained when fluid is in the reservoir.

Another area of concern is the monitoring of line



Graph 2: O_2 Content vs. Time Employing OxyHi©, Prototype and Various Ice Baths

pressure, via a pressure gauge off the bubble trap (Figure 2). The microemboli filter is tested to 600 torr. pressure but only rated at 300 torr. Therefore, we limit our pressure on the Tycos[c] gauge to 350 torr. taking into consideration the pressure drop across the line. We have exceeded this pressure upon occasion (when the cardioplegia catheter was up against the wall of the aorta) and it was necessary to replace the leaking filter before proceeding.

This system does require a source of 100% oxygen and a flowmeter (0-5 L/min range) separate from the pump-oxygenator. We feel that the use of a large volume reservoir, prominently displayed, in conjunction with a hydrophilic filter, provides the safest system we have used yet. Cost of the oxygenated cardioplegia custom pack is approximately $100, which is approximately $50 more than our standard cardioplegia set, but considerably less than using a pediatric bubble oxygenator as some centers have done.

The cardioplegic solution is formulated by the pharmacy containing: 1 L of Plasma-Lyte A, 20 mEq of 8.4% sodium bicarbonate, a total of 25 mEq of potassium chloride and 3 ml of 50% Dextrose. Three liters of solution are formulated for each case. A total of approximately 1400 ml is delivered during an average case with an initial bolus of 1 liter into the aortic root at a flow rate of 250-300 ml/min. Approximately 300 ml are required to prime the system. The system is purged with 100-150 ml to make it bubble free. The third bag of cardioplegia is usually not introduced to the reservoir. Infusion is accomplished by moving a tubing clamp from point B to point A (Figure 2) to move from the recirculate mode to the infuse mode.

Graph 2 shows oxygen content relative to time. With the Oxy-Hi solution being able to carry up to 5.5 vol. % of oxygen compared to only 2 vol. % with our prototype. Calculations of O_2 content were estimated based on extrapolation of the solubility coefficient for *normal saline* when in fact our solution was a PH adjusted saline solution.

In using Table I we arrived at Table II, and the equation:

$$O_2 \text{ content volumes } \% = \frac{\text{ml } O_2}{100 \text{ ml}} = \frac{pO_2 \times \alpha}{\text{barometric pressure}} \times 100$$

where α represents the temperature corrected solubility coefficient of the cardioplegic solution.

Graph 4 shows the short period of time required to elevate the pO_2 of the cardioplegia solution (5-10 minutes) to desired levels. The Oxy-Hi has improved oxygenation time by as much as 100% over our early prototypes.

The highly-oxygenated crystalloid cardioplegia system developed at our institution has been used effectively and safely in over 4000 open heart procedures to date. In its development, some logical questions have arisen in the course of our evaluation of the new system. Using this technique, the possibility of gas coming out of the solution was theorized. This was not seen in the laboratory or clinically on a macroscopic level. Since abandoning the "syringe" technique, the surgeons no longer introduce macroscopic bubbles of air in the root or down the coronary grafts. We feel use of a 0.45 micron filter prevents inadvertent emboli from reaching the heart.

Measurement of pO_2 of the solution was done routinely in the early stages of development and higher O_2 flows (4-5 L/min) were used. However, as seen from Graph 3 and 4, a relatively low gas flow and short amount of time is needed to elevate the pO_2 to desired levels. We no longer get routine pO_2 analyses of this solution. Today in 1987 we use an oxygen flow set at .5 L/min to achieve these pO_2s.

Finally, we were not impressed with the insulating qualities of the American Bentley ice bath stirrer[b] so we now employ an insulated ice chest with a mixture of ice and alcohol which facilitates preservation of our ice for up to 4 hours. Graph 1 (Rate of Cooling of Cardioplegic Solution) notes the mixtures we tested to achieve optimal temperatures. Our investigation shows agitation of the ice bath is necessary to achieve temperatures in the 3-5 °C range. This is done periodically during the case. Alcohol should not be added to the bath until the solution is recirculating through the aluminum coil. This prevents any "icing" of the cardioplegic solution.

c Tycos Corp., Asheville, NC 28801

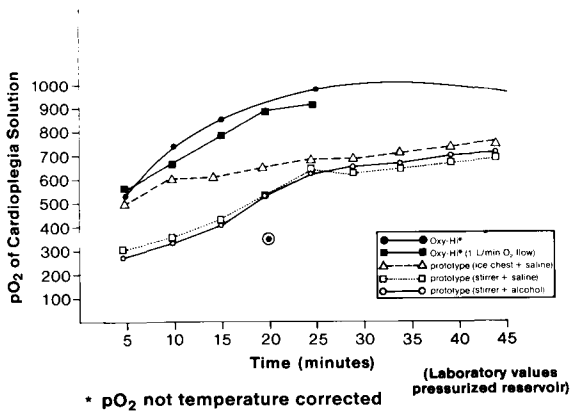
Table 1
Solubility Coefficients of Oxygen in Physiological Solutions
Solubility Coefficient ∝: milliliters of gas dissolved per milliliter of fluid at 760 mmHg pressure.

	O_2 Solubility Coefficient						
	NaCl[1]		Whole Human Blood[2]				
Temp °C	0.119.N	0.155N	Human Plasma	5 g Hb-100 ml-1	10 g Hb-100 ml-1	15 g Hb-100 ml-1	20 g Hb-100 ml-1
10	0.03715	0.03689	0.0338	0.0346	0.0348	0.0352	0.0361
11	0.03631	0.03605	0.0330	0.0338	0.0340	0.0344	0.0353
12	0.03550	0.03524	0.0322	0.0331	0.0333	0.0337	0.0345
13	0.03472	0.03446	0.0315	0.0324	0.0326	0.0330	0.0337
14	0.03399	0.03373	0.0308	0.0317	0.0319	0.0323	0.0330
15	0.03328	0.03302	0.0302	0.0310	0.0312	0.0316	0.0323
16	0.03216	0.03235	0.0296	0.0303	0.0305	0.0309	0.0316
17	0.03196	0.03170	0.0290	0.0297	0.0299	0.0303	0.0310
18	0.03133	0.03107	0.0285	0.0292	0.0294	0.0297	0.0304
19	0.03074	0.03048	0.0281	0.0287	0.0289	0.0292	0.0298
20	0.03015	0.02989	0.0277	0.0282	0.0284	0.0287	0.0293
21	0.02957	0.02931	0.0273	0.0277	0.0279	0.0282	0.0288
22	0.02901	0.02875	0.0269	0.0273	0.0275	0.0277	0.0283
23	0.02847	0.02821	0.0265	0.0269	0.0271	0.0273	0.0279
24	0.02794	0.02768	0.0261	0.0265	0.0267	0.0269	0.0275
25	0.02744	0.02718	0.0257	0.0261	0.0263	0.0265	0.0271
26	0.02696	0.02670	0.0253	0.0257	0.0259	0.0261	0.0267
27	0.02649	0.02623	0.0249	0.0253	0.0255	0.0257	0.0263
28	0.02604	0.02578	0.0246	0.0249	0.0251	0.0253	0.0259
29	0.02562	0.02536	0.0242	0.0245	0.0247	0.0249	0.0255
30	0.02521	0.02495	0.0238	0.0241	0.0243	0.0245	0.0251
31	0.02487	0.02461	0.0234	0.0238	0.0239	0.0242	0.0247
32	0.02454	0.02428	0.0230	0.0235	0.0236	0.0238	0.0243
33	0.02420	0.02394	0.0226	0.0232	0.0233	0.0235	0.0240
34	0.02387	0.02361	0.0223	0.0229	0.0230	0.0232	0.0237
35	0.02353	0.02327	0.0220	0.0226	0.0227	0.0229	0.0234
36	0.02326	0.02300	0.0217	0.0223	0.02442	0.0226	0.0231
37	0.02299	0.02273	0.0214	0.0220	0.0221	0.0223	0.0228
38	0.02273	0.02247	0.0212	0.0217	0.0218	0.0220	0.0225
39	0.02246	0.02220	0.0210	0.0214	0.0215	0.0217	0.0222
40	0.02219	0.02193	0.0208	0.0211	0.0212	0.0214	0.0219
41	-	-	-	-	-	-	-
42	-	-	-	-	-	-	-

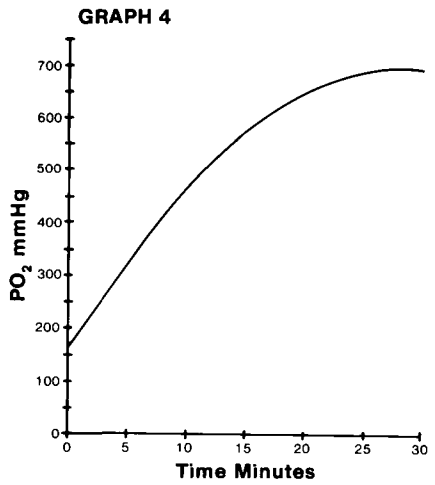
From: Respiration and Circulation, F.A.S.E.B., 1971

Conclusion

Clinical evaluation of oxygenated versus non-oxygenated cardioplegia shows no advantage with cross clamp times under thirty minutes. However, for times greater than thirty minutes, oxygenated cardioplegia showed significant benefit in decreased CPK levels versus the unoxygenated cardioplegia.[4] Development of the Oxy-Hi cardioplegia system from the animal lab to clinical use took a relatively short time (3 months). However, refinements are still taking place over 3 years later. The next step involves comparing this technique to oxygenated blood cardioplegia which will once again require altering our system; such as returning to either a PVC coil or a stainless steel coil and devising an adequate filter for the solution. In the genesis of any product, safety and simplicity should be the foundation for development; in this case, taking existing components to assemble a "new" system, in order to deliver greater amounts of oxygen to the myocardium. In addition, as noted in Graph 3, pO_2s greater than barometric pressure were recorded due to use of a pressurized cardiotomy system. We do not use or recommend the pressurized system and remove one of the luer-lok caps on the reservoir prior to adding oxygen to our system.



Graph 3: Comparison of pO_2 vs. Time of Prototype, Oxy-Hi© and Various Ice Baths
Recirculation Rate = 300 cc/min
Oxygen Flow Rate = 4 L/min



Graph 4: Oxygen partial pressure (pO_2 mmHg) vs. time (min.) for the CAS-2500 OxyHi Reservoir with an O_2 flow rate of 1.5 L/min and a cardioplegia flow rate of 330 ml/min. The temperature of the cardioplegic solution was maintained at 2 °C. From: Bentley Laboratories, 1985.

Table II

Extrapolation of Solubility Coefficients
of Oxygen from Table I for H_2O and NaCI (0.119N)

Temp °C	H_2O	NaCI 0.119N	
0	0.04889	0.04802	
1	0.04758	0.04671	
2		0.04546	
3	0.04512	0.04425	
4	0.04397	0.04310	
5	0.04287	0.04200	Extrapolation
6	0.04180	0.04093	
7	0.04080	0.03993	
8	0.03983	0.03896	
9	0.03891	0.03804	
10	0.03802	0.03715	

**Respiration and Circulation, FASEB 1971

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