A Hemodilution Cardioplegia and a Proposed Delivery System

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We have previously reported our studies of blood cardioplegia and our delivery system for it (1, 2). Our experimental results showing blood cardioplegia to be superior to asanguineous cardioplegia were reported recently (3, 4), and we have used blood cardioplegia for the past two and a half years. Although our clinical results have been gratifying, and the whole blood cardioplegia system was designed with simplicity and patient safety in mind (Fig. 1), there were a number of practical and physiologic limitations to the whole blood cardioplegia delivery system as we have used it (Table I). The two principal practical limitations were the need for two pumps and a cardioplegic reservoir with only a one liter capacity. The sequestering of blood into the cardioplegic reservoir led to the need to recirculate the blood cardioplegic mixture constantly, to keep the contents mixed, as well as a constant flow through the heat exchanger to avoid rewarming. The prime of the extracorporeal circuit had to be increased to compensate for the volume removed temporarily from this circuit in order to make the cardioplegic mixture. Furthermore, the need to alternate clamps to draw and recirculate was slightly cumbersome. The principal physiologic limitation of a whole blood (greater than 20%) cardioplegic system is that the level of hypothermia had to be limited to avoid the potential of blood sludging, which might occur at lower temperatures.

To avoid these practical and physiologic problems, we desired a more simplified system which would allow the incorporation of hemodilution to a) reduce blood viscosity and b) to allow the blood cardioplegic solution to be delivered at a colder temperature. The colder temperature would provide the added physiologic dividend of reducing the potassium concentration needed to produce arrest, as well as delay the time to cardiac rewarming and restoration of spontaneous electrical mechanical activity when the cardioplegic solution is washed away by non-coronary blood flow.

One method of achieving a practical and simplified delivery system would be to dilute the blood in the extracorporeal circuit (hematocrit 20–25%) with an equal volume of cardioplegic solution. This would produce a hemodilution blood cardioplegia with a hematocrit of 10–13%. This hemodilution blood cardioplegia solution could then be cooled to a temperature of 8–10°C with less potential danger of sludging.

Before considering ways to deliver such a cold hemodilution cardioplegic solution in a simple practical way, we needed to be sure, a) that the oxygen requirements of an arrested heart could be met by hemodilution cardioplegic solution with a hematocrit 10°C and b) that myocardial function after a two hour period of aortic clamping was at least as good as when whole blood cardioplegia was used.

To determine the oxygen requirements of the arrested heart, oxygen uptake was measured at the time of induction of blood cardioplegic arrest, and again at 20 and 40 minutes when the solution was reinfused. The results of these measurements are shown in Figure 2, and demonstrate that the very low oxygen uptake at the initiation of cardioplegic arrest (0.3 cc/100g/min) is not constant. Oxygen uptake rises markedly when the

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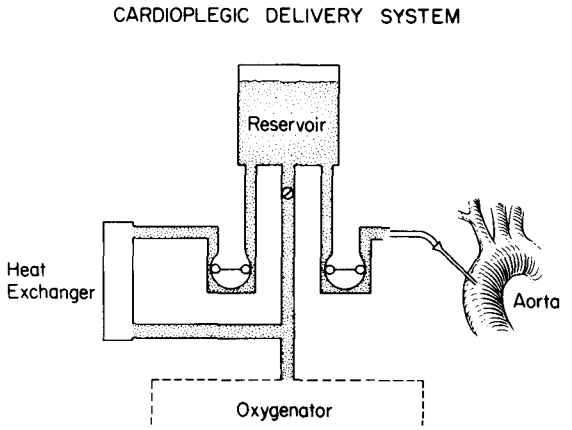

FIGURE 1. Cardioplegia Delivery System

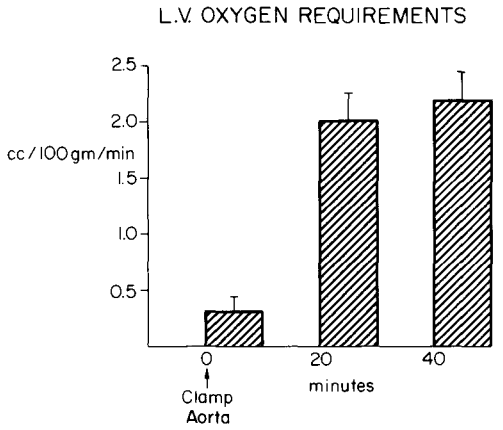

FIGURE 2. Left Ventricular Oxygen Uptake

reinfusion is given at 20 and 40 minutes. This increased oxygen uptake persisted at each 20 minute reinfusion up to two hours. We suspect the 2-3 cc/100g/min oxygen uptake during the time of reinfusion reflects the oxygetive metabolism needed to restore the energy levels depleted in the preceeding 20 minutes intervals of arrest. Figure 3 shows the calculated oxygen delivered to the heart by a standard 300 cc cardioplegic infusion of asanguineous, hemodilution, and whole blood cardioplegia versus the oxygen needs. It is apparent that the oxygen needs of the arrested heart during cardioplegic reinfusions cannot be met by asanguineous solution, but could be met easily with a hemodilution blood cardioplegia or with whole blood cardioplegia. It is furthermore apparent that the whole blood cardioplegia delivers oxygen far in excess of requirements.

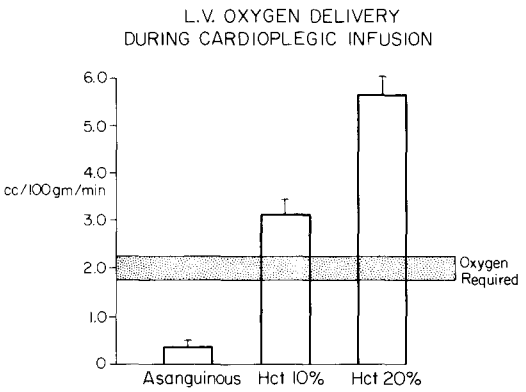

FIGURE 3. Left Ventricular Oxygen Delivery during Cardioplegic Infusions

To test the effect of hemodilution blood cardioplegia on left ventricular performance, a standard blood cardioplegic tubing system was used to withdraw 500 ml of blood from the extracorporeal circuit. This was then mixed with 500 ml of cardioplegic solution to produce 1000 ml of hemodilution blood cardioplegic solution with the concentrations indicated in Table II. The temperature of the blood hemodilution cardioplegic solution was then lowered to 8 ± 2°C by circulating it through the heat exchanger and 200 cc

TABLE I.
Whole Blood Cardioplegia Limitations

- 2 pump heads
- 5 minute infusion delay
- 1 liter capacity
- Pump prime increased
- Only 16-18°C
- Recirculation required
- Multiple clamps

TABLE II.
Hemodilution Blood Cardioplegia

ADDITIVE	mL	COMPOSITION
• 5% dextrose 1/4 N. saline . .	.422	• Osmolarity 360 mos/kg
• KCL 2 meq/ml . .	10	• K^+. . . . 22 meq/L
• THAM	72	• pH. . . . 7.8
• CPD	6	• Ca^{++}. . . 0.3 meq/L
• Diluent volume	500	
• Blood HCT 22%	500	• HCT . . . 10%

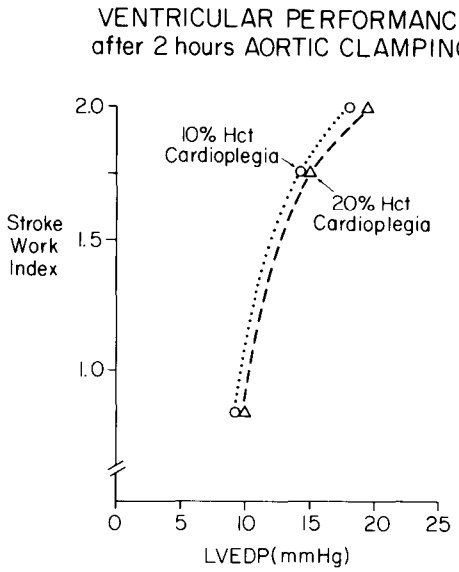

FIGURE 4. Ventricular Performance after 2 Hours Aortic Clamping

of the solution was infused every 20 minutes during the period of aortic clamping.

Thirty minutes after the aortic clamp was removed (2 hours of cardioplegic arrest), left ventricular function was measured compared to the function of hearts protected with whole blood cardioplegia (Figure 4). There were no functional differences in left ventricular performance with hemodilution blood cardioplegia as compared to whole blood cardioplegia.

The delivery system for the clinical use of hemodilution blood cardioplegia solution (as we envision it) is shown in Figure 5. The diluent would be a 1000 ml bag of I.V. solution with appropriate cardioplegic additives. This would result in a 1225 ml diluent and when mixed with an equal volume of blood from the extracorporeal circuit results in 2.5 liters of hemodilution blood cardioplegia. By using comparable size tubings an equivalent mixture of both solutions would result. The heat exchanger, to be acceptable, would need a performance factor of 0.75 and a flow rate of 200 ml/min. Since a single rollerhead is the only hardware required, we feel the system would be easily adaptable to any pump oxygenator in current clinical use.

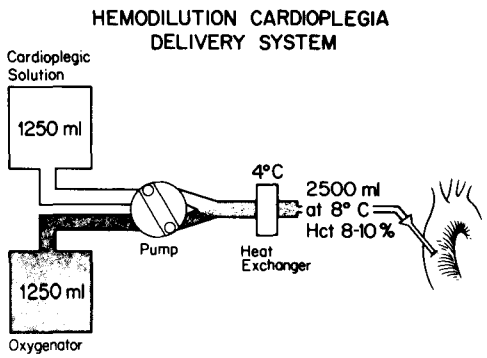

FIGURE 5. Hemodilution Cardioplegia Delivery System

TABLE III.
Hemodilution Blood Cardioplegia Advantages

Physiologic	Practical
∘ 8-10°C	∘ Deeper hypothermia ∘ Delayed rewarming
∘ Less K^+	∘ Larger infusion volumes ∘ Better distribution ∘ More cooling

Compared with whole blood cardioplegia, hemodilution blood cardioplegia would have a number of advantages that would make it desirable for clinical use (Table III). The physiologic advantages include the colder cardioplegic temperature and the lowering of the potassium concentration necessary to produce arrest. This provides the practical advantages of a larger infusion volume which could be given with the same total amount of potassium delivered to the patient. The larger infusion volumes in colder temperatures would result in better distribution of the cardioplegic solution (especially through coronary stenoses) and more cooling of the myocardium. Additionally, the 2.5 liter volume delivery cardioplegia would require only one bag of diluent to be used for most clinical cases.

References

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