A Modified Blood Cardioplegia Delivery System Designed to Provide Improved Right Heart Protection

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Abstract

Inadequate right heart protection during cardiac surgery with extracorporeal circulation is a complex problem. Rewarming of the right heart via collateral coronary blood flow, ambient room air, surgical lights and the proximity of the heart to other mediastinal structures, as well as inadequate initial cooling are some of the factors sited as causes of reduced myocardial protection. Recently there has been increased attention to the problem especially in the setting of adequate left heart protection. The goals of this paper are 1) To review and discuss the literature addressing right heart dysfunction and associated abnormalities of cardiac rhythm, 2) To explore the etiology of these complications and 3) To describe a newly designed system of right heart protection utilizing a modified blood cardioplegia delivery system which we feel will be helpful in reducing the incidence of these complications.

Introduction

Historically the focus of hypothermic cardioplegia for myocardial protection has been the preservation of left ventricular function. The importance of achieving this goal need not be emphasized to the surgeon or perfusionist confronted by a patient with compromised myocardial function. Considerable time and effort is usually required to wean him from cardiopulmonary bypass and a stormy post operative course often follows. During this period the assistance of the intra-aortic balloon pump or some other such aggressive invasive modality is often necessary. Even with the use of such heroic efforts too many of these patients die. Fortunately, the frequency of this event has been greatly reduced by the development and implementation of advances in surgical and perfusion theory and technique. With these advances now a part of our practice we can direct our focus to solving some of the more ellusive and less common problems and complications that are associated with cardiopulmonary bypass. Post-operative right ventricular dysfunction and peri-operative conduction disturbances are two such complications.

Until recently it has been presumed that the right ventricle is less susceptible to peri-operative ischemic damage. Likewise, it was thought that such damage, when it occurred, could be well tolerated by volume loading the patient. However, recent studies indicate neither of these assumptions to be true.[1,2,3,4,5,6,7,8] The frequency with which significant right heart dysfunction occurs, as measured by ejection fraction, has been reported at about 38 percent.[9]

The incidence of peri-operative conduction disturbances, i.e., supraventricular tachyarrythmias, and varying degrees of atrio-ventricular block, has been reported to be as high as 40 percent.[10] The etiology of this complication has been attributed to the exquisite sensitivity to ischemia of the heart's conductive tissue relative to other myocardial tissues.[11] Since the sinus node, inter-atrial and internodal pathways and the atrio-ventricular node are located in the right atrium the argument has been proposed, when conduction abnormalities occur, that we have not provided adequate myocardial preservation for that region of the heart.

It is the purpose of this paper to review and discuss recent medical literature that suggests we are not successfully protecting either right ventricular or right atrial function. We will also describe a modified blood cardioplegia delivery system designed to provide augmented right heart preservation.

Literature Review

In 1979 Rosenfeldt et al,[12] utilizing a porcine heart model, described the effects of various heat sources on myocardial rewarming during hypothermic cardioplegic arrest. The factors studied were 1) Pulmonary and systemic venous return and the effect of atrial cannulation technique, 2) Systemic body temperature

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and conducted heat via the pericardium and other mediastinal structures, 3) Heat convection via ambient room air and 4) Radient heat via surgical lights. Their findings indicated that dual caval cannulation resulted in ventricular sepal and atrio-ventricular nodal region temperatures that were 11°C and 9°C cooler, respectively, than those achieved when a single atrial cannulation technique was utilized. The effects of conducted heat via other mediastinal structures was limited to the posterior left ventricle and left atrium. This factor was also dependent on the patient's systemic temperature, and pump flow rate. The increase in temperature of the affected areas was only 2 degrees centigrade at a systemic temperature of 23 degrees centigrade and flow rate of 1.6 $l/m^2/min$ of body surface area. Systemic temperatures of 37°C and flow rates of 2.4 $l/m^2/min$ of body surface area increased temperatures in these regions by as much as 12°C. Convection via ambient room air resulted in a 2.7–4.7°C increase in right atrial and right ventricular wall temperatures, radiant heat gain was limited to 1.5°C. The effects of convection and radiation could be essentially eliminated by the use of external iced saline lavage. They further suggested dual caval cannulation, adequate systemic hypothermia (28 degrees centigrade or less) and reduced perfusion flow rates to minimize the rewarming effect. Despite the implementation of all these precautions significant right-left heart temperature differentials were still observed.

Fisk et al[13] in 1982 evaluated the differences in right and left ventricular temperatures in 130 consecutive patients undergoing cardiopulmonary bypass for various procedures. Dual caval cannulation, systemic temperatures of 23°C and topical iced saline lavage of the heart were all utilized. During these procedures 1,010 data points were collected comparing right and left ventricular temperatures. Following the delivery of 500–1000 ml. of hypothermic cardioplegic solution at 8°C or colder and at pressures up to 120 mmHg. the mean right to left ventricular temperature gradient was 6°C with the largest difference being 19°C. The authors implicated this persistent gradient as an indication of potential inadequate right heart protection and as a major factor in peri-operative right ventricular failure. Gonzales et al[14] in 1985 using a canine model quantified the effect on right ventricular function of varying degrees of right-left ventricular temperature gradients. All dogs were placed on cardiopulmonary bypass and were exposed to 60 minutes of hypothermic cardioplegic arrest. During this period the left ventricle was continuously maintained at 15°C while the right ventricle was permitted to vary according to the assignment to one of three groups: Group I, 15°C; Group II, 25°C; Group III, 35°C. Using multiple indicies, right ventricular function was examined pre-bypass and at 15, 30, 45 and 60 minutes post-bypass. Following the ischemic period and completion of all measurements the right ventricular function in Group I (15°C) did not vary significantly from pre-operative measurements. In Group II (25°C) 25 percent of the dogs died while the remaining 75 percent had significant and unresolving right ventricular dysfunction. Group III (35°C) experienced the poorest results. Seventy-five percent of the dogs died and the other 25 percent displayed severe right ventricular dysfunction. The authors warn that failure to maintain the right ventricular temperatures at less than 25°C during ischemic arrest invites almost certain peri-operative dysfunction.

Tchervenkov et al[9] studied 30 consecutive patients undergoing coronary artery bypass to evaluate right heart function, via changes in its ejection fraction, following surgery. All patients had normal ventricular function pre-operatively. Significant dysfunction was evident in 30 percent of the patients at 24 hours post-operatively and 23 percent continued to have significant reductions in right ventricular ejection at one week.

In 1983 a series of articles by various groups focused on the problem of peri-operative cardiac dysrhythmias and their relationship to inadequate right heart preservation. Tchervenkov et al,[10] while studying the heart's electrical behavior during and following hypothermic cardioplegic arrest in 25 patients undergoing elective coronary artery bypass grafting, found that in spite of continuous ventricular electromechanical arrest the frequency of atrial activity was much greater than anticipated. Comparing the electrical activity recorded on standard electrocardiographic leads vs. that found on bipolar atrial electrograms they observed that standard electrocardiographic monitoring is frequently not sensitive enough to detect the atrial activity which was recorded by the electrograms. In fact, 23 of the 25 patients displayed atrial activity during cardioplegic arrest using the atrial electrogram, while significantly fewer had peripheral electrocardiographically sensed activity. The group further observed a direct relationship between the length of atrial activity during the aortic cross clamp period and post-operative supraventricular tachyarrhythmias. All 6 of 23 patients (22 percent) with atrial activity greater than 25 minutes developed this complication. To further verify this finding they commissioned another study[15] of 50 elective coronary artery bypass patients. In this group 44 of the 50 patients exhibited sustained atrial activity. Fifteen of the 44 (35 percent) developed post-operative supraventricular tachycardia. Once again, the significant co-factor was the length of time atrial activity was present during the "arrest" period. The length of cross clamp time was not found to be significant. The group concluded that right atrial protection in the patients with persistent atrial activity was inadequate even though ventricular activity was abolished in all instances.

Similar results were generated by Ferguson et al[16] using a canine model. They developed a very sophisticated monitoring scheme to evaluate myocardial electrical activity and utilized it as a method of assessing the quality of myocardial preservation. This scheme included 25 intramural electrodes, 3 epicardial reference electrodes, a HIS Bundle catheter and 3 peripheral electrodes. Following hypothermic cardioplegic arrest the origin of myocardial electrical activity, when it occurred was determined to be the lower atrial septum. Occasionally, this activity was conducted through the atrio-ventricular node resulting in a ventricular response. This activity was not detectable on standard peripheral electrocardiographic leads. In concurrent patient studies 3 of 23 patients exhibited this type of ventricular activity. Two of three required intra-aortic balloon pump support and all three required pharmacologic support in the post-operative period.

In addition to right ventricular dysfunction and post-operative supraventricular tachycardia Smith et al[17] noted in eight coronary artery bypass graft patients some degree of post-operative atrio-ventricular conduction block. All eight of these patients experienced difficulties in cooling the right atrium (mean temperature 25.9°C ± 1.3°C) in contrast to the ventricular septum (mean temperature 15.7°C ± 1.3°C). Elaborating on these observations they designed a canine model in which differential distribution of cardioplegic solution was implicated as the etiology of the disparity between right atrial and ventricular septal temperatures. All of the dogs in which this disparity occurred developed atrio-ventricular conduction delays. To resolve the occurrence of inadequate right heart preservation Smith et al[18] developed a protocol to augment right atrial hypothermia. This canine model compared electrophysiologic data from a control group (40 minutes of hypothermic cardioplegic arrest using a standard technique) and that generated by the experimental group (similar to control except atrial hypothermia was augmented by intra-cavitary or specialized topical techniques). The control group mean atrial septal temperature was 27.4°C ± 1.2°C while the study protocol achieved a mean atrial septal temperature of 20.8°C ± 3.3°C. Post-operative disturbances in atrio-ventricular conduction were observed in all control dogs while none of the study group developed this complication.

In a similar study Novick et al,[19] using a porcine model, compared the effectiveness of four techniques of myocardial protection 1) Single atrial cannulation and standard cardioplegic technique, 3) Dual caval cannulation, cardioplegia and continuous extra cavitary right atrial (4°C) saline irrigation and 4) Dual caval cannulation, cardioplegia and continuous intracavitary right atrial (4°C) saline irrigation. Right atrial and right ventricular temperatures were as follows: Group 1, 27 ± 0.5°C and 20.5 ± 0.4°C; Group II, 25.3 ± 0.5°C and 19.1 ± 0.4°C; Group III, 22.8 ± 0.4°C and 19.0 ± 0.3°C; and Group IV, 17.0 ± 0.5°C and 17.5 ± 0.3°C. Left heart temperatures did not change significantly except in Group IV where they fell sharply. Measurement of atrial electrical activity in these groups provided similar results. The mean duration of atrial activity during the arrest period decreased from 50.2 ± 5.5 minutes in Group I to 8.0 ± 3.9 minutes in Group IV.

Description of a Modified Blood Cardioplegia Delivery System

Taking our lead from the lessons learned in these studies we designed a modified blood cardioplegia delivery system which delivers one liter per minute of cold blood (mean temperature 8°C) into the right atrium on a continuous basis while the aorta is cross clamped (except while delivering doses of cardioplegic solution).

The cardioplegia delivery system used provides a 4:1 blood to crystalloid solution mixture. The components of this system are a stainless steel cooling coil, a 5 micron crystalloid solution filter, bubble trap, temperature monitoring site, pressure monitoring site, and appropriate tubing. Modifications to this system which permit recirculation of the crystalloid solution and delivery of cold blood to the right atrium are two ⅛ × ⅛ × ⅛ Y connectors, a one foot section of ⅛ inch inner diameter tubing, one ¼ × ¼ × 3/16 Y connector and two 8 foot lengths of ¼ inch inner diameter tubing (Figure 1). The administration of cardioplegia to the aortic root is accomplished by clamping the right

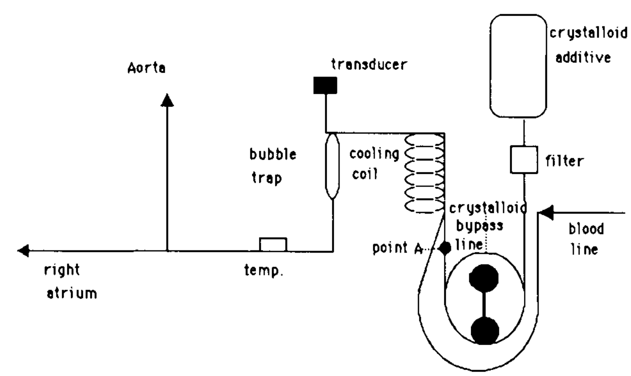

Figure 1: Modified blood cardioplegia delivery system. Point "A" is point at which clamp is placed during delivery of cold blood to the Right heart. The crystalloid bypass line is clamped during delivery of blood cardioplegia. A clamp must be placed on one line or the other but not both.

atrial delivery line and the crystalloid solution bypass line. Delivery of cold blood to the right atrium is accomplished by clamping the aortic root line and the positive pressure side of the crystalloid solution line at point A. Cannulation of the right atrium is accomplished with an angled vent catheter containing multiple ports to prevent excessive jet-streaming of the blood at a delivery rate of one liter per minute.

Immersion of the stainless steel coil in an iced saline bath and using a single pass cooling technique permits delivery of blood or cardioplegia at a mean temperature of 8°C. We are currently developing a recirculation cooling system which should permit even more efficient cooling. Several cautions are in order. First, this system can only be used when a single atrial cannula and a closed right heart are present. Second, the perfusionist must observe the patient's systemic temperature carefully. The augmented right atrial cooling results in continuous cooling of venous return blood. To counter this problem our heater-cooler is kept on 30°C once the desired degree of systemic hypothermia is achieved. Third, the blood delivered to the right atrium is oxygenated. This causes venous blood gas samples taken from the venous return line to be inaccurate.

Initial observations comparing the use of the modified system vs. the standard system indicate a reduction in the occurrence of atrial electrical activity during the arrest period. We have also recorded lower right ventricular temperatures. The incidence of peri-operative conduction disturbances has been reduced. We intend to continue our observations and to quantify our results in a later study.

Discussion

Hypothermic cardioplegic arrest for cardiac surgery has proven very effective in providing preservation of the left ventricle in the vast majority of cases. A review of current medical literature indicates that this same degree of protection is often not provided for the right atrium and right ventricle. We have reviewed the etiologic factors contributing to the problem and have described a modified blood cardioplegia delivery system which upon initial observation has improved right heart preservation. We recognize that further study of this system is necessary and we intend to quantify our findings in a later publication.

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Questions from the Audience

Question—Sandra Pfefferkorn: Did you try anything less than a liter per minute to accomplish this reduction in temperature in the right atrium?

Answer: No.

Question—Frank Hurley: My question relates to the elevations that one might expect in the potassium. Did you see this type of elevation on bypass? If so, how did you adjust for it?

Answer: There really wasn't an elevation in potassium, because the additive, the potassium-containing solution, was essentially being recirculated. When you gave the continuous cold blood to the right atrium, you clamped the additive line, allowed the additive to recirculate, and only gave cold blood.

Question—LeRoy Ferries: You did mention for clarification, to use a two stage in the IVC. I wonder why two stage, and a cannula in the SVC that slings down. Why the two stage in the IVC?

Answer: You need to be able to pick up that liter per minute of cold blood and you do that with the basket portion of the two stage cannula.