ORIGINAL ARTICLE

Predictable Spontaneous Beating in 96% of Coronary Bypass Operations

William I. Brenner, MD, FACS

Kaiser Foundation Hospital
Los Angeles, CA

Keywords: Blood cardioplegia, spontaneous beating, cardioversion, coronary bypass, myocardial protection

Abstract

To determine the incidence of spontaneous beating in isolated coronary bypass operations, one cardiac surgeon's experience with 677 consecutive cases over an 8 1/2 year period (1980-1988) was studied. Myocardial protection included hypothermic (4°C) blood cardioplegia containing procaine and papaverine, topical cooling (4°C) and systemic hypothermia (25°C). During warming, 100 mg of lidocaine was administered when body temperature reached 30°C. Six hundred fifty-one patients (96%) had spontaneous beating after removal of the aortic cross-clamp following completion of distal anastamoses. Electrical cardioversion was required immediately in 26 of these 677 patients (4%) and in an additional 32 (5%) later in the operation, usually when ventricular fibrillation was induced by manipulation of the beating heart to inspect the distal anastamoses. Therefore, 619 of these 677 coronary bypass patients (91%) were spared intraoperative electrical cardioversion and its potential for myocardial damage.

Introduction

Disappointment with the protection provided by crystalloid cardioplegia in high risk patients prompted the author to switch to blood cardioplegia containing procaine and papaverine and administer lidocaine during warming beginning January 30, 1980. The gratifying observation of spontaneous beating upon release of the aortic cross-clamp in nearly all coronary bypass operations contrasted sharply with only a 50% approximate incidence with the previous technique and prompted this study. Results are reported on 677 consecutive elective and emergency isolated coronary bypass operations, including 25 repeat coronary bypass operations performed by one surgeon over an 8 1/2 year period (Jan. 30, 1980-Aug. 15, 1988). During the same time frame, the author also performed combined procedures in 126 patients. Results with coronary bypass plus valve replacement in 110 patients and coronary bypass with left ventricular aneurysmectomy in 16 patients are presented as well.

Address correspondence to: William I. Brenner MD, 1505 N. Edgemont St., Los Angeles, CA 90027.

Materials and Methods

All patients were members of a large health maintenance organization (The Kaiser Permanente Medical Care Program of Southern California). This regionalized practice of cardiac surgery with a traditionally conservative referral pattern by general practitioners, internists, and cardiologists tends to result in cardiac surgical candidates with advanced coronary artery disease. The patient profile was evolving during the years of the study (Table 1). However, the greater incidence of spontaneous beating in the 677 patients was consistent in spite of a seemingly worse patient profile, which included more elderly patients, more female patients, more operations following recent myocardial infarction, more urgent (rather than elective) operations, more repeat coronary bypass operations, more use of the internal mammary artery (a longer operation) and, for the first time, emergency operations for failed angioplasty. The incidence of spontaneous beating was consistent in the 677 patients, despite a rise in the use of coronary endarterectomy as an adjunct to revascularization, increasing from one in six patients in the early part of the series to one in two patients in the latter part of the series. Left main coronary artery stenosis of greater than 50% was present in nearly one in six patients in the early part of the series, declining to one in 10 patients in the latter part of the series as indications for coronary revascularization were liberalized. The number of grafts per patient averaged 3.3, declining from 3.4 early in the series to 3.1 later in the series. This decline is attributed to fewer target arteries present in repeat coronary bypass candidates as well as fewer target arteries in patients requiring coronary bypass operation for failed angioplasty, usually performed for single or double vessel coronary disease. Reoperation coronary bypass comprised 3.7% of the series (25 patients) increasing from 2% early on to 7% more recently. This category is known to have a higher risk profile than initial coronary bypass patients especially since the patients were older and most often had advanced triple vessel disease at the time of their initial coronary bypass operation, performed at an average age of 58 years. This experience contrasts with other reports on reoperation coronary bypass, in which the typical patient profile is an individual whose initial coronary bypass operation was performed at age 50 years or less for single or double vessel coronary artery disease.

Surgical Technique

After initiation of cardiopulmonary bypass with an ascending aortic cannula and a single venous two-stage cannula inserted via the right atrial appendage, the patient is core cooled to 25°C and the arterial blood temperature is cooled to 16-18°C. With this degree of cooling, approximately one in three patients sustains ventricular fibrillation, while the remainder have profound bradycardia. The aorta is cross-clamped and blood cardioplegia suspension, prepared in the heart lung machine with the Shiley BCD™ (a) apparatus, is infused into the aortic root with a DLP™ (b) plastic cannula. An aliquot of blood cardioplegia suspension is taken up onto the operative field for hand injection into the saphenous vein graft segments following completion of distal anastamoses. Along with the initial 600 ml dose of blood cardioplegia, 100 mg of 4°C procaine hydrochloride is injected into the aortic root. Left heart vents are employed in less than 10% of cases--usually for unexplained cardiac distention or prophylactically for patients with ejection fractions below 25%. In the absence of the Shiley BCD™ apparatus, blood cardioplegia suspension can be prepared on the operative field using a 50/50 mix of pump blood and a predetermined crystalloid cardioplegia solution, once the patient has been placed on cardiopulmonary bypass. Three hundred ml of 25% human albumin (Albuminar 25, Armour Pharmaceuticals) (c) is added to the Isolyte-S prime of the pump to prevent the colloid osmotic pressure of the cardioplegia suspension from dropping too low. The blood cardioplegia suspension is buffered with THAM to achieve an alkalotic pH. It contains 500 mg/l of methylprednisolone and 100 mg/l papaverine. The patient also receives 2 grams of methylprednisolone intravenously at the start of the operation. Table 2 gives the final composition of the blood cardioplegia suspension as delivered to a typical adult male patient. In female patients with lower starting hematocrits, bank blood may be added to the pump prime to prevent excessive hemodilution with a goal of maintaining a hematocrit greater than 20% on cardiopulmonary bypass. In patients with impaired renal function or in patients with oliguria during cardiopulmonary bypass unresponsive to diuretics or low dose dopamine, a hemoconcentrator (Dow™) (d) or similar device is utilized in the bypass circuit to remove excess crystalloid and potassium. Topical hypothermia with 4°C normal saline is by continuous drip irrigation and removal by suction catheters for red cell salvage using the cell saver (Haemonetics™) (e) or BRAT™) (f) device for return to the pump circuit directly or by intravenous infusion into the patient. The ECG is initially silenced to "flat line" with approximately 600 ml of blood cardioplegia suspension at 4°C. After completing each distal anastamosis, 100-200 ml is reinfused into the aortic root and an additional 100 ml given by hand injection through the saphenous vein segments using syringes. The total dose of blood cardioplegia suspension for a typical triple or quadruple bypass is 1.5 to 2.0 liters achieving a septal temperature of 10 to 12°C. The potassium content of the blood cardioplegia suspension is not intentionally varied at subsesquent reinfusions during the cross-clamp period. Warming of the patient is begun as the final distal anastamosis is started. When 30°C core body temperature is attained, 100 mg of lidocaine is given, usually preceeding removal of the aortic cross-clamp by several minutes. When the cross-clamp is removed, spontaneous beating occurs within 30 to 60 seconds. When used as a conduit, the left internal mammary artery is usually attached to the left anterior descending coronary artery as the last of the distal anastamoses, for reasons of safety and logistics. Initiation of mammary artery flow into the left anterior descending coronary artery occurs before removal of the aortic cross-clamp and most often this alone causes the heart to begin beating spontaneously. In nearly all instances of spontaneous beating, the initial rhythm is atrioventricular dissociation; however, regular sinus rhythm was established in nearly all patients before they left the operating room. Although temporary pacing wires are placed on all patients, their use is rarely required.

a. Shiley, Inc. Irvine, CA.
b. DLP, Inc., Grand Rapids, MI
c. Armour Pharmaceuticals, Inc., South Plainfield, NJ
d. Dow Corning, Inc., Midland, MI
e. Haemonetics, Inc. Braintree, MA
f. Cobe Laboratories, Inc., Arvada, CO

Results

Of a total of 677 patients in the study group, 651 (96%) had spontaneous beating, 26 (4%) had ventricular fibrillation and required immediate electrical cardioversion, and 32 (5%) had spontaneous beating initially and then later in the operation required electrical cardioversion for ventricular fibrillation, usually induced by manipulation of the heart when displacing it to inspect distal anastamoses and ensure hemostasis. Therefore, 619 (91%) of these 677 patients never required intraoperative electrical cardioversion while 58 (9%) did (Table 3). Included in these 677 patients are 25 patients who underwent repeat isolated coronary bypass operation. Of these, 23 (92%) had spontaneous beating, two (8%) had ventricular fibrillation requiring immediate electrical cardioversion. Another three (12%) had spontaneous beating initially and then later cardioversion. Hence, 20 of the 25 (80%) repeat coronary bypass patients never required intraoperative electrical cardioversion while five (20%) did (Table 4). During the same time frame (1980-1988), an additional 110 patients (not included in the 677 of the main study group) underwent combined coronary bypass and valve replacement procedures. Eighty-six patients (78%) had spontaneous beating, 24 (22%) had ventricular fibrillation requiring immediate electrical cardioversion, and 25 (23%) had spontaneous beating initially but later in the operation required electrical cardioversion. Hence, only 61 patients (55%) of this group of 110 undergoing combined coronary bypass and valve replacement never required electrical cardioversion while 49 (45%) did (Table 5). During the same time frame (1980-1988), an additional 16 patients (not included in the 677 of the main study group) underwent combined coronary bypass and left ventricular aneurysmectomy procedures. All 16 had spontaneous beating. Three patients (19%) had spontaneous beating initially and then required electrical cardioversion for

Table 1

PROFILE OF 677 ISOLATED CORONARY BYPASS PATIENTS

Timeframe: January 30, 1980 - August 15, 1988

Average Number of Grafts per Patient	3.3 3.4 Early in Series 3.1 Later in Series
Revascularization Including Coronary Endarterectomy	Early in Series 1 of 6 Later in Series 1 of 2
Patients with Left Main Coronary Artery Stenosis >50%	Early in Series Approx. 1 of 6 Later in Series Approx. 1 of 10
Reoperation Coronary Bypass	25/677 (3.7%)
Revascularization with Left Internal Mammary Artery	50/677 (7.4%) None Early in Series Approx. 1 of 3 Later in Series
Revascularization After Failed Angioplasty	15/677 (2.2%) None Early in Series All 15 Later in Series

Table 2

TYPICAL COMPOSITION OF BLOOD CARDIOPLEGIA SUSPENSION

Hematocrit	12%
pH	8.0
p02	440 mm Hg
Glucose	630 mg%
Potassium	31 mEq/L
Calcium	5.2 mg%
Osmolality	352 mOsm
Colloid Osmotic Pressure	6.1 U.

Table 3

BLOOD CARDIOPLEGIA

Isolated CABG
1980-1988

	N	(%)
Total Patients	677	(100%)
Spontaneous Beating	651	(96%)
Ventricular Fibrillation Immediate Cardioversion	26	(4%)
Spontaneous Beating Later Cardioversion	32	(5%)
Total Requiring Cardioversion	58	(9%)
Total Never Requiring Cardioversion	619	(91%)

Table 4

BLOOD CARDIOPLEGIA

Repeat Isolated CABG
1980-1988

	N	(%)
Total Patients	25	(100%)
Spontaneous Beating	23	(92%)
Ventricular Fibrillation Immediate Cardioversion	2	(8%)
Spontaneous Beating Later Cardioversion	3	(12%)
Total Requiring Cardioversion	5	(20%)
Total Never Requiring Cardioversion	20	(80%)

ventricular fibrillation later in the operation. Hence, 13 of 16 patients (81%) never required electrical cardioversion in this group (Table 6). The high incidence of spontaneous beating contrasted sharply with an incidence of spontaneous beating of approximately 50% in the previous 177 consecutive patients undergoing isolated coronary bypass operation by the same surgeon during the preceeding 3 1/2 year period (Aug. 11, 1976-Jan. 25, 1980). During this time, crystalloid cardioplegia without procaine, papaverine, and lidocaine was the method of myocardial protection. Improved clinical results, including reduced requirement for inotropic and mechanical support in high risk patients and lower operative mortality, were also noted.

Discussion

Spontaneous beating after removal of the aortic crossclamp is one confirmation of good myocardial protection during the period of aortic crossclamping and cardiac arrest (2). Spontaneous beating confirms that high energy phosphate stores, nutrients, mitochondrial and cell membrane integrity were preserved during a period of potential ischemic injury. This study describes a clinical technique which consistently achieves nearly universal spontaneous beating without electrical cardioversion in isolated coronary bypass operations. To a lesser degree, the technique achieves spontaneous beating in a significant majority of cases where coronary bypass is combined with valve replacement and left ventricular aneurysmectomy.

Ventricular fibrillation is a particularly dangerous rhythm in patients with stenosis of the coronary arteries (3, 4, 5). Subendocardial ischemia can occur as a result of ventricular fibrillation, especially in the hypertrophied myocardium, as is the case in many candidates for coronary bypass operation who suffer from hypertensive heart disease with ventricular hypertrophy. In the presence of flow critical coronary stenosis, transmural pressure can exceed perfusion pressure, causing blood to be shunted away from the subendocardium. Since most coronary revascularization procedures involve performing the distal anastamoses first, the myocardium is extremely vulnerable to ischemic injury until flow is initiated through the saphenous vein grafts. This is particularly true if the rhythm is ventricular fibrillation, which has been shown to increase myocardial oxygen consumption over that of a beating heart supported with cardiopulmonary bypass. Lockerman and associates (4) demonstrated a less than perfect (75%) correlation between CK-MB release and time in ventricular fibrillation. The authors suggest that other factors such as left ventricular venting, retrograde coronary sinus perfusion and revascularization strategies may alter the pattern of reperfusion ventricular fibrillation and CK-MB balance. Other potential deleterious consequences of the triad of ventricular fibrillation, internal cardiac massage and electrical cardioversion in coronary bypass operations are listed in Table 7 and include thermal myocardial injury due to the electrical current of cardioversion and mechanical disruption of distal anastamosis integrity by the trauma of internal cardiac massage and cumbersome and bulky cardioversion paddles, especially in patients with hearts that are difficult to access (6, 7, 8).

Disruption of the smooth flow of a coronary bypass operation when microsurgical techniques such as performing the proximal anastamoses are compromised by the macrosurgical interventions of internal cardiac massage and electrical cardioversion with defibrillator paddles. Confidence in this technique allows the clutter of defibrillator paddles on the operative field to be eliminated during routine coronary bypass operations. Although available in the operating room, defibrillator paddles are not usually opened and passed onto the operating field in routine isolated coronary bypass operations. They are, however, on the operating field for all cases involving poor left venticular function, reoperation coronary bypass, combined valve replacement and left venticular aneurysmectomy cases. Cardioplegia delivery is suboptimal across critical coronary stenosis, particularly when the artery is totally occluded in the absence of well-established coronary collateral circulation (9, 10). One of the rationales for the superiority of blood cardioplegia suspension to crystalloid cardioplegia solutions in protecting the myocardium with flow critical coronary stenosis is the superior flow of sanguinous compared to asanguinous fluids across flow critical stenosis. This is due to increased shunting of low viscosity asanguinous solutions away from areas supplied by arteries with flow critical stenoses (11, 12, 13). Sanguinous cardioplegia suspensions with higher viscosity are more uniformly distributed to areas supplied by coronary arteries with flow critical coronary stenoses. Hence, delivery of the myocardial protective substrates and oxygen is enhanced by the blood vehicle. That the observed 96% incidence of spontaneous beating in isolated coronary bypass operations is not due solely to the use of blood versus crystalloid cardioplegia is confirmed by the need for frequent electrical cardioversion from venticular fibrillation in the hands of others employing blood cardioplegia (2).

Reduction of the potassium content has been reported to reduce the incidence of postoperative AV block. Some groups have gone so far as to have completely eliminated potassium from the reinfusion blood cardioplegia suspension (14, 15, 16, 17). In the series reported here, the potassium content of the reinfusion blood cardioplegia suspension was not changed in any way from that of the initial dose. New conduction defects are an extremely nonspecific finding for perioperative myocardial infarction. Other investigators have cautioned against reduction of the potassium content in subsequent reinfusion aliquots, fearing a deterioration in myocardial protection in the absence of high potassium--especially in those patients with extensive non-coronary collateral circulation who are prone to washout of the blood cardioplegia suspension and its myocardial protection. A recent publication confirms the additive value of mild systemic hyperkalemia ($K \geq 5.1$ mEq/l) in preventing ventricular fibrillation. The authors noted enhanced protection from ventricular fibrillation when mild hyperkalemia is combined with prophylactic lidocaine. 200 mg of lidocaine was administered three minutes before removing the aortic crossclamp (18). The onset of spontaneous beating in

the series reported here with bradycardic atrioventricular dissociation as the initial rhythm may enhance the functional recovery of the myocardium in a manner akin to that seen after secondary blood cardioplegia (11, 19). Until flow is initiated through all the conduits, no attempt is made to stimulate the heart rate either by mechanical prodding, electrical pacing, or by the infusion of chronotropic catecholamines. Again, only rare patients required temporary ventricular pacing and no patient among the 677 in this series has required a permanent pacemaker insertion in the perioperative period for persistent heart block.

Aggressive topical hypothermia with several liters of 4°C normal saline by continuous pericardial irrigation is very likely to contribute to myocardial protection. Topical ice slush is never employed for fear of inducing epicardial frostbite injury and phrenic nerve palsy. In spite of not using a pericardial insulating jacket, no patient in this series of 677 suffered phrenic nerve palsy as a result of topical 4°C normal saline. Magilligan and associates described a technique to prevent warming of the conduction system during cardiopulmonary bypass (20). It involves snaring both cannulated cava and continuously irrigating the interior of the right atrium with iced saline. Unfortunately, this cumbersome technique is not practical for routine clinical use. Since spontaneous beating and stable sinus rhythm at the time of completion of the proximal anastamoses is the rule in the series reported here, it also appears to be unnecessary. In 1937, Beck and Mautz described the protective effects of procaine in preventing cardiac arrhythmias during cardiac surgery (mostly pericardiectomy operations) (21). In 1983, subsequent investigators documented the markedly enhanced incidence of spontaneous beating with freedom from ventricular fibrillation in hearts protected by procaine and lidocaine (22-23). However, these same authors became discouraged by the myocardial depression they observed and believed it to be induced by these powerful local anesthetics. They noted that a high percentage of their hearts required inotropic stimulation to permit weaning from cardiopulmonary bypass and therefore could not justify the adjunctive use of procaine and lidocaine in clinical coronary bypass operations.

It appears, however, that 100 mg of procaine, as employed in this series (instilled with the initial dose of blood cardioplegia suspension), followed by 100 mg of lidocaine (during warming at 30°C core temperature), has resulted in a nearly universal incidence of spontaneous cardioversion progressing rapidly to normal sinus rhythm. Inotropic support is employed in low doses on occasion probably more to counteract the effects of beta and calcium channel blocking drugs (which are routinely continued up to and including the morning of operation) than for the reversal of myocardial depression induced by procaine and lidocaine which appears to be dose related and need not have a deleterious effect on the outcome of the procedure. Newer drugs in the procaine-lidocaine Class IC anti-arrhythmic agent family such as flecainide may have a role in protecting the myocardium in the future as more is learned about them (24).

The internal mammary artery was not used as a conduit in the early part of this series. Although the author has subsequently begun to employ it in carefully selected patients (50 by the time the study was concluded), the use of the internal mammary artery poses a problem with the operative strategy of protecting the most seriously jeopardized regions of myocardium first, along with the need to protect the regions of the left venticle, the interventicular septum and the anterior wall; most critical in terms of power production. These power regions are supplied by the usual target for the internal mammary artery, namely, the left anterior descending coronary artery, which unfortunately is most often bypassed as the final distal anastamosis. The author is certain that this situation, the anastamosis of the left internal mammary artery to the left anterior descending coronary artery following the completion of less important but logistically safer distal anastamoses, has resulted in the power areas of the left ventricle remaining ischemic, especially when the artery is 100% occluded, unless well-established collaterals from other coronary arteries are present. Reperfusing an ischemic septum and anterior wall with normothermic unmodified blood from the mammary artery (considered the "ideal" conduit because of its superior long-term patency rate and proven ability to enlarge in response to demand), which may itself be on the small side or in spasm may result in a disastrous outcome for the patient as described in a recent clinical report (25).

In one series, the internal mammary artery, as well as saphenous veins, was employed in 15 out of 20 patients undergoing isolated coronary bypass grafting (4). Fewer than 25% of patients did not require electrical cardioversion from ventricular fibrillation.

The authors of the report speculate as to the causes for the direct correlation between the time the patient spends in ventricular fibrillation and the magnitude of the release of the CK-MB band of cardiac muscle isoenzyme. They concede that even in the absence of transmural myocardial infarction, prolonged ventricular fibrillation probably causes subendocardial necrosis and CK-MB release is its marker.

The inability to protect the distribution of the LAD first with blood cardioplegia, as is possible with saphenous vein grafts, is the major shortcoming of employing the internal mammary artery in a multiple bypass graft case, and this is especially true when the LAD is totally occluded. As recommended by several authors in an attempt to address this problem, the author has begun to perfuse the the LAD first with an arteriotomy and a small Teflon™ (g) catheter (DLP™)(b), instilling blood cardioplegia (26, 27). Following completion of the other distal anastamoses with saphenous veins, the internal mammary artery is sutured to the LAD. Retrograde infusion of blood cardioplegia, either through the coronary sinus or into the right heart with the pulmonary artery cross-clamped, is also in clinical practice in an attempt to address the problem (28, 29).

In summary, this report presents a myocardial protection technique and an operative strategy applied to multivessel isolated coronary bypass operations, which is successful in nearly eliminating both time in ventricular fibrillation and potentially harmful internal massage, emergency venting, and electrical defibrillation from the conduct of a routine coronary

g. E.I. Dupont de Nemours and Co., Wilmington, DE

Table 5

BLOOD CARDIOPLEGIA

CABG + Valves
1980-1988

	N	(%)
Total Patients	110	(100%)
Spontaneous Beating	86	(78%)
Ventricular Fibrillation Immediate Cardioversion	24	(22%)
Spontaneous Beating Later Cardioversion	25	(23%)
Total Requiring Cardioversion	49	(45%)
Total Never Requiring Cardioversion	61	(55%)

Table 6

BLOOD CARDIOPLEGIA

CABG + LV Aneurysmectomy
1980-1988

	N	(%)
Total Patients	16	(100%)
Spontaneous Beating	16	(100%)
Ventricular Fibrillation Immediate Cardioversion	0	(0%)
Spontaneous Beating Later Cardioversion	3	(19%)
Total Requiring Cardioversion	3	(19%)
Total Never Requiring Cardioversion	13	(81%)

Table 7

POTENTIAL DELETERIOUS CONSEQUENCES OF THE TRIAD OF VENTRICULAR FIBRILLATION, INTERNAL CARDIAC MASSAGE AND ELECTRICAL CARDIOVERSION IN CORONARY BYPASS OPERATIONS:

1. Subendocardial ischemia due to cardiac distention in non-vented hypertrophied hearts necessitating cardiac venting on an urgent basis.

2. Thermal myocardial injury due to the electrical current of cardioversion.

3. Mechanical disruption of distal anastamosis integrity by internal cardiac massage and cardioversion paddles.

4. Disruption of smooth flow of microsurgical proximal anastamosis performance by macrosurgical interventions of internal cardiac massage and electrical cardioversion.

5. Clutter of cardioversion paddles on operative field during routine coronary bypass operation.

revascularization procedure, an operation which constitutes the bulk of "open heart surgery" in the United States. The data presented here on spontaneous beating are less impressive in the 110 patients who had concomitant coronary revascularization and valve replacement operations. This is not surprising, in light of the more advanced heart disease of longer duration and usually markedly hypertrophied and/or scarred myocardia of patients suffering from combined valvular and coronary artery disease. Although the numbers are small, the 16 patients undergoing coronary bypass operations combined with left ventricular aneurysmectomy and the 25 patients undergoing repeat coronary bypass operations have an incidence of spontaneous beating approaching that for initial isolated coronary bypass operations.

References

1. Brenner WI. A simple and inexpensive system for preparing blood cardioplegia for pediatric open-heart operations. *Proceedings of the People to People Delegation to the People's Republic of China.* 1985.
2. Roberts AJ, Woodhall DD, Knauf DG, et. al. Coronary artery bypass graft surgery: Clinical comparison of cold blood potassium cardioplegia, warm cardioplegic induction, and secondary cardioplegia. *Ann Thorac Surg.* 1985; 40: 483-487.
3. Fall SM, Burton NA, Graeber GM, et. al. Prevention of ventricular fibrillation after myocardial revascularization. *Ann Thorac Surg.* 1987; 43: 182-184.
4. Lockerman ZS, Rose DM, Cunningham JN, et. al. Reperfusion ventricular fibrillation during coronary artery bypass operations and its association with postoperative enzyme release. *J Thorac Cardiovasc Surg.* 1987; 93: 247-252.
5. Khuri SF, Marston WA, Josa M, et. al. Observations on 100 patients with continuous intraoperative monitoring of intramyocardial pH: The adverse effects of ventricular fibrillation and reperfusion. *J Thorac Cardiovasc Surg.* 1985; 89: 170-182.
6. Dahl CF, Ewy GA, Warner ED, et. al. Myocardial necrosis from direct current countershock. Effect of paddle electrode size and time interval between discharges. *Circulation* 1974; 50: 956.
7. Doherty PW, McLaughlin PR, Billingham M, et. al. Cardiac damage produced by direct current countershock applied to the heart. *Am J Cardiol.* 1979; 43: 225-232.
8. Rubio PA, Farrell EM. Lower energy direct defibrillation of the human heart following cardioplegic arrest. *Texas Hrt Inst J.* 1983; 10: 143-144.
9. Grondin CM, Helias J, Vouhe PR, et. al. Influence of a critical coronary artery stenosis on myocardial protection through cold potassium cardioplegia. *J Thorac Cardiovasc Surg.* 1981; 82: 608-615.
10. Hilton CJ, Teubl W, Acker M, et. al. Inadequate cardioplegic protection with obstructed coronary arteries. *Ann Thorac Surg.* 1979; 28: 323-334.
11. Buckberg GD. Progress in myocardial protection during cardiac operations. *Cardiovasc Clin.* 1984; 12: 9-30.
12. Engleman RM, Ronson JH, Dobb W, et. al. The superiority of blood cardioplegia in myocardial preservation. *Circulation.* 1980; 62:(Suppl I) 62-66.
13. Shapira N, Kirsh M, Jochim K, et. al. Comparison of the effect of blood cardioplegia to crystalloid cardioplegia on myocardial contractility in man. *J Thorac Cardiovasc Surg.* 1980; 80: 647-655.
14. Ellis RJ, Mavroudis C, Gardner C, et. al. Relationship between atrioventricular arrhythmias and the concentration of K^+ ion in cardioplegic solution. *J Thorac Cardiovasc Surg.* 1980; 80: 517-526.
15. Baerman JM, Kirsh MM, deBuitleir M, et. al. Natural history and determinants of conduction defects following coronary artery bypass surgery. *Ann Thorac Surg.* 1987; 44: 150-153.
16. Tchervenkov CI, Wynands JE, Symes JF, et al: Electrical behavior of the heart following high-potassium cardioplegia. *Ann Thorac Surg .* 1983; 36: 314-319.
17. Tucker WY, Ellis RJ, Mangano DT, et. al:.Questionable importance of high potassium concentrations in cardioplegic solutions. *J Thorac Cardiovasc Surg.* 1979; 77: 183-190.
18. Praeger PI, Kay RH, Moggio R, et. al. Prevention of ventricular fibrillation after aortic declamping during cardiac surgery. *Texas Hrt Inst J.* 1988; 15: 98-101.
19. Addetia AMG, O'Reilly BF, Walsh GWM, et. al. Prolonged asystole during intraoperative myocardial perfusion: An experimental study. *Ann Thorac Surg.* 1988; 45: 482-488.
20. Magilligan DJ Jr., Deepak V, Peper W, et. al. Failure of standard cardioplegic techniques to protect the conducting system. *Ann Thorac Surg.* 1985; 39: 403-408.
21. Beck, CS and Mautz, FR. The control of the heartbeat by the surgeon with special reference to ventricular fibrillation occurring during operation. *Ann Surg.* 1937; 106: 525-537.
22. Tchervenkov CI, Symes JF, Wynands JE, et. al. Lidocaine as an adjunct to high potassium cardioplegia: A prospective randomized clinical trial. *Surg Forum.* 1983; 34: 319-321.
23. Takamoto S, Levine FH, LaRaia PJ, et. al. Effect of procaine in crystalloid and blood potassium cardioplegia solutions. *J Surg Res.* 1980; 29: 497-509.
24. Brunsting LA, Jessen ME, Abd-Elfattah AS, et. al. Myocardial protective effects of the class Ic antiarrhythmic agent flecainide. *J Thorac Cardiovasc Surg.* 1987; 94: 904-910.
25. Sarabu MR, McClung KA, Gass A, et. al. Early postoperative spasm in left internal mammary artery bypass grafts. *Ann Thorac Surg.* 1987; 44: 199-200.
26. Mindich BP, Jurado RA, Estioko MR et. al. Administering cold cardioplegia in patients undergoing coronary artery bypass grafting. *Ann Thorac Surg.* 1981; 31: 188-190.
27. Lee ME. Selective intracoronary cardioplegia: An adjunct to retrograde coronary sinus cardioplegia. *Ann Thorac Surg.* 1988; 46: 712.
28. Buckberg GD. Studies of controlled reperfusion after ischemia. When is cardiac muscle damaged irreversibly? *J Thorac Cardiovasc Surg.* 1986; 92: 483-487.
29. Diehl JT, Eichhorn EJ, Konstam MA et. al. Efficacy of retrograde coronary sinus cardioplegia in patients undergoing myocardial revascularization: A prospective randomized trial. *Ann Thorac Surg .* 1988; 45: 595-602.

This paper was peer reviewed (in original form) for publication in the Journal of Extra-Corporeal Technology.