

Coronary Artery Bypass Graft with Minimal Extracorporeal Circulation

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ABSTRACT

Background: To evaluate the advantages and benefits of a minimized extracorporeal circulation system in the performance of coronary artery bypass grafts.

Methods: From September 2000 to February 2003, 279 consecutive patients underwent isolated coronary artery bypass grafting with minimal extracorporeal circulation. A group of 243 patients at good risk as defined by a EuroSCORE of 3 underwent complete bypass and blood cardioplegia, and a high-risk group of 45 patients (EuroSCORE, 6) underwent operations with partial assistance and a beating heart. In a prospective substudy analysis of thrombocyte and platelet counts, transfusion requirements, PaO₂/FIO₂, leukocyte count, C-reactive protein level, postoperative bleeding, intensive care unit stay, and ventilation, 40 patients from the good-risk group were matched and compared with 40 patients who underwent operations with a conventional extracorporeal system.

Results: Revascularization was complete with a mean of 2.8 distal anastomoses in the good-risk group and 2.4 in the high-risk group. Mortality rates were 1.2% and 4%, respectively. The system provided either complete or partial bypass assistance and depended on preload and afterload. The system also allowed easy access to all territories with perfect hemodynamic stability. Priming was reduced to 400 mL, and arterial and venous saturation monitoring revealed excellent maintenance of pH values. No complications or failure of the system occurred. Hemodilution, inflammatory response, and transfusion requirements were reduced in the minimal extracorporeal circulation group.

Conclusions: Minimal extracorporeal circulation allows minimal hemodilution and reduces transfusion requirements. The method allows safe and complete revascularization of either an arrested or a beating heart.

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INTRODUCTION

Open cardiopulmonary bypass (CPB) with cardioplegic arrest remains the gold standard for performing complete coronary revascularization but is associated with several effects related to aortic cross clamping and CPB that are of concern in certain high-risk patients. CPB is conducive to a multitude of pathogenic mechanisms responsible for postoperative morbidity [Hammerschmidt 1981]. However, we are increasingly presented with higher-risk patients. Off-pump coronary artery bypass (OPCAB) has been described as a means of decreasing both mortality and morbidity in high-risk [Bergsland 1997] and low-risk patients [Cartier 2000]. This procedure allows easy access to the anterior aspect of the heart. The most common procedure in the OPCAB series has been left internal mammary artery grafting to the left anterior descending artery through sternotomy or limited anterior thoracotomy [Calafiore 1998]. When the circumflex territory is grafted, OPCAB causes hemodynamic instability and reduces coronary artery blood flow [Gründeman 1998] mainly owing to extreme tilting of the heart [Nierich 2000]. Because OPCAB is technically demanding, some concerns have been raised about the quality of anastomosis and long-term patency [Pagni 1997]. Some authors describe use of an axial blood flow pump for CABG on a beating heart [Lönn 1999]. These techniques have the advantage of allowing CABG without risk of CPB, but reaching the marginal branches of the circumflex artery remains difficult [Lönn 1999]. Instability, when it occurs, is generally linked to right-heart failure, which cannot be treated with this technique. To provide good stability without compromising hemodynamics in beating heart surgery, we tested a minimal extracorporeal circulation (MECC) system. We also tested the system in complete bypass with cardioplegia to decrease hemodilution and the inflammatory response to CPB. Our concept involves modification of both the bypass circuit and surgical technique. We describe our initial experience with this technique.

MATERIAL AND METHODS

From September 2000 to February 2003, a total of 634 patients underwent CABG in our institution. Among these, 279 consecutive patients underwent CABG with MECC; all were operated on by the same surgeon. The patients were divided into 2 groups. One group of 45 patients, defined as being at high risk by EuroSCORE, were operated

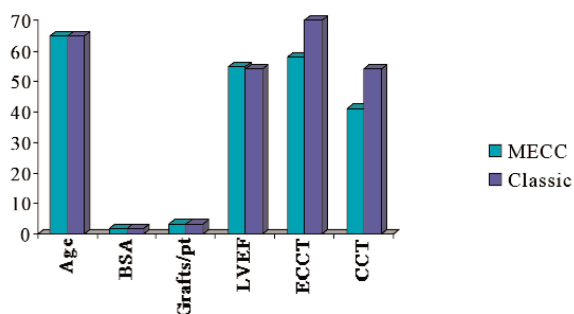


Figure 1. Preoperative and operative characteristics of 40 patients operated on with a minimal extracorporeal circulation (MECC) system and 40 patients with a classic open bypass system. BSA indicates body surface area; LVEF, left ventricular ejection fraction; ECCT, extracorporeal time; CCT, cross-clamp time.

on with beating heart technique. MECC was used for assistance in reducing hemodynamic instability during lifting of the heart. The other group, 234 good-risk patients, underwent CABG with blood cardioplegia and MECC. Patients in this group participated in a substudy in which 40 patients operated on with MECC were matched for risk factors and compared with 40 patients operated on with a conventional open system with reservoir and roller pump and priming of 1500 mL. For the 2 groups in the substudy, we specifically analyzed and compared thrombocyte count, platelet count, $\text{PaO}_2/\text{FIO}_2$, leukocyte count, C-reactive protein level, amount of postoperative bleeding, transfusion requirements, intensive care unit stay, and ventilation time.

During the same time period, 76 patients with coronary arteries easily accessible by sternotomy (essentially left anterior, diagonal, and right coronary arteries) underwent off-pump procedures and therefore were not included in this study.

All patients were treated according to our routines for preoperative and postoperative care. The patients were mechanically ventilated with a mixture of oxygen and air (Servo ventilator 900; Siemens, Munich, Germany). Anesthesia was maintained with sufentanil (Sufenta), midazolam (Hypnovel), and pancuronium bromide (Pavulon). A central venous pressure line was placed in 3 patients to allow continuous hemodynamic monitoring and mixed venous oxygen saturation. Midline sternotomy was performed.

The MECC device is a closed system that consists of a centrifugal pump head (MECC system; Jostra, Hirlingen, Germany), an integrated heat exchanger oxygenator, an arteriovenous loop, a priming and recirculation line, a pressure and sampling port, an arterial and 2-stage venous cannula, and 500 mL of priming solution (Figure 1). We did not use left ventricular vent, cardiectomy suction, or venous reservoir. All components were completely coated with an active heparin biocompatible coating (Bioline Coating System; Jostra).

The surgeon administered heparin (250 U/kg) directly into the atrium prior to performing the proximal anastomoses. After the saphenous vein and/or mammary artery were dissected, the proximal anastomoses were performed under partial aortic cross clamping. Additional doses were given before the system was started and were guided by an

activated clotting time (ACT) not less than 400 seconds. All procedures were performed at normothermia. The MECC system was placed as close as possible to the patient by the right side of the chest to reduce line to a minimum.

MECC as Assistance in Beating Heart Procedures

Ventilation was maintained throughout the procedure. We started CPB by raising the circuit pressure above the patient's systemic pressure, and we continued partial cardiopulmonary support. In all cases we maintained a mean blood pressure above 70 mm Hg during CPB. During bypass we monitored hematocrit, ACT, line pressure, blood gases, and patient parameters: arterial blood pressure, central venous pressure, temperature, and diuresis. Revascularization was done sequentially, starting with the culprit lesion when the patient was operated on in unstable condition or starting with the left mammary artery on the left anterior descending artery when the patient was in stable condition. Once all anastomoses were completed, MECC was slowly stopped while the patient's filling and systemic pressures were optimized. All aspirated blood and the complete contents of the arterial and venous lines were returned to the patient with a cell saver.

All distal-vessel anastomoses were done on a beating heart. Our technique of distal anastomosis on a beating heart involved the help of a cardiac stabilizer. As soon as distal anastomoses were completed, flow to the native coronary artery was established to perfuse the revascularized territory during bypass. For all patients we recorded preoperative variables (see Appendix) to calculate a European score. Hemodynamic recordings were made during CPB. We placed a mixed venous saturation pulmonary artery catheter in 3 patients for measurement of continuous mixed venous saturation. Blood chemistry data were obtained the day before the operation and on the subsequent postoperative days. To determine heart muscle damage, we measured the enzyme troponin I.

MECC with Cardioplegia

In this procedure total calculated flow (2.2 L/m^2) was reached progressively, and blood cardioplegia was given in the aortic root as an initial dose and repeated doses after each distal anastomosis. Before declamping, warm blood was given at a rate of 300 mL/min to wash out cardioplegia solution for 3 minutes. The procedures were performed in the manner described above.

Statistics

For statistical nomenclature and data analysis, we followed the "Guidelines for Data Reporting and Nomenclature" published in the *Annals of Thoracic Surgery*. Descriptive statistics were used to summarize the data in terms of mean, median, and range, and a *t* test was used to compare groups.

Patient Population

Demographic and preoperative data for the 2 groups of patients are shown in Table 1. Six (13%) of the patients were operated on in cardiogenic shock, and an intraaortic balloon pump was placed prior to surgery. One patient with an ejection fraction of 20% was in cardiac arrest after failed angioplasty

Table 1. Preoperative Data*

Demographics	Beating Heart	Cardioplegia
No. of patients	45	234
Men, n (%)	35 (77)	171 (73)
Mean age, y	67.3 ± 8.8 (range, 41-87)	65.2 ± 11.2 (range, 34-78)
Stable angina, n (%)	12 (26)	211 (90)
Unstable angina, n (%)	33 (74)	23 (10)
Myocardial infarction (<7 d), n (%)	16 (35)	24 (10)
Cardiogenic shock, n (%)	6 (13)	0
Preoperative left EF, %	36.6 ± 13.6	50.4 ± 9.4
EuroSCORE	5.8 ± 2.7	3.5 ± 2.2
Body surface area, m ²	1.8 ± 0.1	1.8 ± 0.2

*EF indicates ejection fraction; EuroSCORE, European system for cardiac operative risk evaluation.

and was immediately placed on cardiac support. He underwent single saphenous vein grafting to the left anterior descending artery and was weaned off CPB with low-dose dobutamine.

RESULTS

Intraoperative data are listed in Table 2. Total priming was 500 mL, which allowed the intraoperative hematocrit to remain elevated during bypass with minimal transfusions required. Several complications occurred and are described in Table 3. The 40 patients operated on with MECC and cardioplegia were compared with 40 patients operated with an open classic system. The preoperative and operative characteristics are given in Figure 1. In the MECC group a decrease in extracorporeal circulation time was caused by construction of venous anastomoses prior to bypass, a procedure not done in the classic group. Tables 3 and 4 reveal there was a higher hematocrit during bypass in the MECC group and a lower rate of intraoperative transfusion. Platelet count was higher in

Table 2. Intraoperative Data

Intraoperative Data	Beating Heart (n = 45)	Cardioplegia (n = 234)
Mean no. of grafts per patient	2.4 ± 0.8 (range, 2-5)	2.8 ± 0.7 (range, 2-4)
No. of arteries bypassed	114	655
Left anterior descending, n (%)	40 (89)	234 (100)
Diagonal, n (%)	12 (30)	42 (18)
Marginal branches of circumflex, n (%)	30 (67)	231 (98)
Right coronary, n (%)	32 (72)	229 (98)
Double bypass, n (%)	41 (91)	42 (18)
Triple bypass, n (%)	1 (2)	18 (7)
Quadruple bypass, n (%)	64.2 ± 26.2	58.8 ± 17.3
Bypass time, min	42.2 ± 14.3	42.2 ± 14.3
Aortic cross-clamp time, min	34.7 ± 5.1	36.7 ± 5.1
Preoperative hematocrit, %	31.1 ± 4.9	31.6 ± 4.7
Perioperative hematocrit, %	4 (8)	5 (2)
Perioperative transfusion, n (%)		

the MECC group on days 1 and 2 postoperatively. C-reactive protein level was markedly decreased in the MECC group as measured on postoperative days 1, 2, 3, and 4. There were no differences in the 2 groups in regard to leukocyte count, FIO₂/PaO₂, ventilation time, and intensive care unit stay.

Revascularization was as complete as possible, and the bypass system allowed either complete cardiopulmonary support or partial support with pulsatile arterial pressure. Mean bypass flow was 2.5 ± 0.9 L/min (range, 0.5-5.3 L/min), for a mean body surface area of 1.82 ± 0.1 m².

The mean venous pressure recorded during the procedure was 4.5 ± 2.8 mm Hg and varied in the beating heart group depending on the location of the grafts. Arterial and venous blood gases were monitored throughout the procedure and remained within normal range. Mixed venous saturation remained normal during bypass on beating hearts (Figure 2).

Before discharge, 2 patients underwent postoperative angiography because of angina. One patient had a dilated small posterior descending artery. The other patient, who had undergone prior left pneumonectomy and irradiation, had a dilated left main artery. All grafts and anastomoses were patent.

DISCUSSION

For some high-risk patients, OPCAB may decrease postoperative morbidity and mortality [Ascione 1999]. However, this initial advantage of OPCAB has to be carefully evaluated in light of long-term results showing a higher rate of reoperation in OPCAB patients compared with CPB patients with acute myocardial infarction [Locker 2000] or left ventricular dysfunction [Sternick 2000]. The results of these studies and others [Gundry 1998] can be related to incomplete revascularization with OPCAB. This finding is evidenced by the decreased number of marginal bypass grafts performed in beating heart surgery series than in cardioplegia series. This outcome is due in part to difficulty performing distal anastomosis on the circumflex branches through a sternotomy. This difficulty has been well demonstrated in numerous animal [Gründeman 1998] and clinical studies [Nierich 2000]. Tilting the heart reduces venous return and decreases cardiac output. This problem can be partly compensated in patients with "good ventricles" by raising preload (by Trendelenburg

Table 3. Postoperative Data*

Postoperative Data	Beating Heart (n = 45)	Cardioplegia (n = 234)
Ventilation time, h	Median, 7	Median, 5
Intensive care unit stay, h	Median, 48	Median, 36
Troponin I, µg/L	9.9 ± 17.6	3.4 ± 6.9
Inotropic support,* n (%)	11 (24)	5 (2)
Intraaortic balloon, n (%)	5 (11)	
Cerebrovascular event, n (%)	1 (2)	2 (0.8)
Mediastinitis, n (%)	1 (2)	2 (0.8)
No. of deaths (%)	2 (4)	3 (1.2)
Hospital stay, d	8 ± 2	7 ± 2

*Inotropic support includes dobutamine, dopamine, and noradrenaline.

Table 4. Inflammatory Parameters and Hematologic Data*

	Minimal Extracorporeal Circulation		P
	(n = 40)	Standard (n = 40)	
Age, y	67.4 ± 8.3	69.2 ± 5.9	NS
Body surface area m ²	1.78 ± 0.3	1.69 ± 0.4	NS
Left ventricular ejection fraction, %	49.8 ± 8.2	51.5 ± 5.6	NS
Priming, mL	500	1300	.0001
Extracorporeal time, min	57.7 ± 14.6	71.5 ± 15.8	.001
Aortic cross-clamp time, min	38.1 ± 14.1	52.3 ± 10.4	.001
Preoperative hemoglobin, g/dL	12.8 ± 1.7	12.7 ± 2	NS
Perioperative hemoglobin, g/dL	10.5 ± 1.8	8.3 ± 1.7	.0001
Postoperative hemoglobin, g/dL	10.6 ± 1.9	10.5 ± 1.8	NS
Leukocytes day -1	7.5 ± 1.7	7.7 ± 2.1	NS
Leukocytes day +1	13.9 ± 4	14.3 ± 3.8	NS
Leukocytes day +2	13.9 ± 2.9	14.4 ± 4.23	NS
Platelets day -1	259 ± 105	219 ± 50.4	NS
Platelets day +1	233 ± 80.6	192.6 ± 50.9	.03
Platelets day +2	215 ± 85.1	182.3 ± 42.4	NS
CRP day -1	5 ± 0.9	6.2 ± 5.3	NS
CRP day 1	76 ± 39.7	102.1 ± 48.1	.04
CRP day 2	161 ± 52.4	225 ± 70.6	.0008
CRP day 3	154.6 ± 51.8	223.7 ± 64	.0002
CRP day 4	116.8 ± 46.8	167.2 ± 61.3	.0004
Postoperative bleeding/24 h, mL	530 ± 212	575 ± 356	NS
Patients receiving transfusion, n (%)	16 (34)	14 (29.7)	NS
FiO ₂ /PaO ₂ , mm Hg	244	263	NS
Length of ventilation, h	9.3 ± 20.4	10.7 ± 21.9	NS
Intensive care unit stay, h	Median, 48	Median, 48	

*NS indicates not significant; CRP, C-reactive protein.

position and fluid administration) and/or using adjunctive inotropic support during completion of the anastomosis. However, tilting of the heart is extremely poorly tolerated in patients with poor ejection fraction and a dilated heart with no reserve and is usually followed rapidly by heart failure. Therefore, our surgical approach for these patients was based on 2 main objectives: first, we tried to use CPB and aortic cross clamping for as little time as possible to decrease myocardial ischemia; second, we used CPB as assistance to compensate for the decrease in cardiac output during completion of the distal anastomosis to maintain stable hemodynamic values. With the MECC technique, access to all coronary arteries, including the marginal branches, was no longer a problem, because CPB compensated for the decrease in cardiac output, and coronary perfusion was maintained throughout the procedure because systolic-diastolic pressure was maintained. Hemodynamic conditions were stable throughout the operation in our patients, as evidenced by the various hemodynamic and biological parameters studied, and there were no signs of ischemia on the electrocardiogram during bypass. In addition, if stabilization is not optimum for performing good-quality anastomoses, cardioplegia can easily be given for performance of revascularization of the "difficult" territory. Cardioplegia can be followed or preceded by

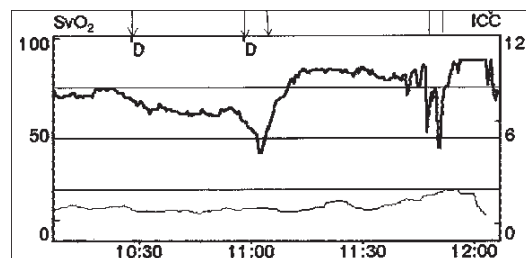


Figure 2. Mixed venous saturation (SvO₂) as recorded with a pulmonary artery catheter in a patient undergoing beating heart surgery. The initial drop is associated with tilting of the heart prior to bypass. During bypass, saturation remains stable. The second drop relates to verification of marginal bypass after bypass was discontinued. D indicates cardiac output; ICC, continuous cardiac index.

revascularization of the other territories with the aorta not clamped to decrease aortic cross-clamping time.

Comparing the MECC system for revascularization with an open classic system of bypass, we noted a reduction in hemodilution, a reduction in inflammatory response, and a reduction in transfusion requirements.

This system probably can be beneficial for older and arteritic patients, who do not tolerate hemodilution well. The MECC system is easily used and safe. If air enters the system, the pump will automatically shut off. It is easy to refill the venous line, and the air will purge itself automatically via the 1-way valve of the oxygenator. Because patients act as their own reservoirs, the pump depends to a great extent on preload and afterload, and the roles of the anesthesiologist and the pump technician are emphasized.

The results of this study need to be confirmed with larger long-term studies.

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APPENDIX

European System for Cardiac Operative Risk Evaluation (EuroSCORE): Risk Factors, Definitions, and Weights (Score)*

	Definition	Score
Patient-related factors		
Age	1 point per 5 years over 60 years	1
Sex	Female	1
Chronic pulmonary disease	Long-term use of bronchodilators or steroids for lung disease	1
Extracardiac arteriopathy	1 or more of the following: claudication, carotid occlusion or >50% stenosis, previous or planned intervention on the abdominal aorta, limb arteries or carotids	2
Neurological dysfunction	Disease severely affecting ambulation or day-to-day functioning	2
Previous cardiac surgery	Requiring opening of the pericardium	3
Serum creatinine	>200 $\mu\text{mol/L}$ preoperatively	2
Active endocarditis	Patient still under antibiotic treatment of endocarditis at time of surgery	3
Critical preoperative state	1 or more of the following: ventricular tachycardia, fibrillation, or aborted sudden death, preoperative cardiac massage, preoperative ventilation before arrival in the anesthesia room, preoperative inotropic support, intraaortic balloon counterpulsation, or preoperative acute renal failure (anuria or oliguria <10 mL/h)	3
Heart-related factors		
Unstable angina	Rest angina requiring intravenous nitrates until arrival in the anesthesia room	2
Left ventricular dysfunction	Moderate or LVEF 30%-50%	1
	Poor or LVEF <30%	3
Recent myocardial infarction	<90 days	2
Pulmonary hypertension	Systolic pulmonary arterial pressure >60 mm Hg	2
Operation-related factors		
Emergency	Carried out on referral before the beginning of the next working day	2
Other than isolated CABG	Major cardiac procedure other than or in addition to CABG	2
Surgery on thoracic aorta	For disorder of ascending, arch, or descending aorta	3
Postinfarction septal rupture		4

*LVEF indicates left ventricular ejection fraction; CABG, coronary artery bypass grafting.