ELSEVIER

European Journal of Cardio-thoracic Surgery 18 (2000) 575–582

EUROPEAN JOURNAL OF CARDIO-THORACIC SURGERY

www.elsevier.com/locate/ejcts

Adult cardiac surgery outcomes: role of the pump type

A. Parolari*, F. Alamanni, M. Naliato, R. Spirito, V. Franzè, G. Pompilio, M. Agrifoglio, P. Biglioli

Department of Cardiac Surgery, University of Milan, Centro Cardiologico, Fondazione I Monzino IRCCS, Via Parea 4, 20138 Milan, Italy

Received 13 June 2000; received in revised form 1 August 2000; accepted 17 August 2000

Abstract

Objective: This study was carried out to evaluate whether the type of pump used for cardiopulmonary bypass (CPB; roller vs. centrifugal) can affect mortality or the neurological outcomes of adult cardiac surgery patients. **Methods**: Between 1994 and June 1999, 4000 consecutive patients underwent coronary and/or valve surgery at our hospital; of these, 2213 (55.3%) underwent surgery with centrifugal pump use, while 1787 (44.7%) were operated on with a roller pump. The effect of the type of the pump and of 36 preoperative and intraoperative risk factors for perioperative death, permanent neurological deficit and coma were assessed using univariate and multivariate analyses. **Results**: The overall in-hospital mortality rate was 2.2% (88/4000), permanent neurological deficit occurred in 2.0% (81/4000) of patients, and coma in 1.3% (52/4000). There was no difference in hospital mortality between patients operated with the use of centrifugal pumps and those operated with roller pumps (50/2213 (2.3%) vs. 38/1787 (2.1%); $P = 0.86$). On the other hand, patients who underwent surgery with centrifugal pumps had lower permanent neurological deficit (34/2213, (1.5%) vs. 47/1787 (2.6%); $P = 0.020$) and coma (20/2213 (0.9%) vs. 32/1787 (1.8%); $P = 0.020$) rates than patients operated with roller pumps. Multivariate analysis showed CPB time, previous TIA and age as risk factors for permanent neurological deficit, while centrifugal pump use emerged as protective. Multivariate risk factors for coma were CPB time, previous vascular surgery and age, while centrifugal pump use was protective. **Conclusions**: Centrifugal pump use is associated with a reduced rate of major neurological complications in adult cardiac surgery, although this is not paralleled by a decrease in in-hospital mortality.

Keywords: Roller pump; Centrifugal pump; Mortality; Neurological outcome

1. Introduction

Neurological injury is one of the most debilitating complications after adult cardiac surgery performed using cardiopulmonary bypass (CPB). Despite a continuous trend towards a decline in overall mortality in adult cardiac surgery, an increase in the average age of patients undergoing cardiac surgery has resulted in a substantial increase in serious adverse neurological events, and in the proportion of related in-hospital deaths[1,2].

Previous studies have assessed the effect of CPB on neurological outcomes in adult patients undergoing cardiac surgery[3–10]; however, little information exists on whether the type of the pump used for CPB (roller vs. centrifugal) can affect the neurological outcomes of adult patients undergoing cardiac surgery.

The aim of this study was to evaluate risk factors for perioperative mortality and adverse neurological outcomes, with special emphasis on the role of using a roller or centrifugal pump for perfusion.

2. Patients and methods

We have retrospectively reviewed the charts of 4000 consecutive patients who, during the period of January 1994–June 1999, underwent coronary and/or valve surgery with the use of CPB at our hospital. Patients who had additional procedures performed (LV aneurysmectomy, carotid endarterectomy, ascending aorta replacement) were excluded from the study.

2.1. Surgical procedure

On the morning of surgery, patients received their usual dose of antianginal drugs, and 2–5 mg morphine and 1 mg atropine as premedication. All patients received a standard moderate dose of fentanyl and benzodiazepine anesthesia,

* Corresponding author. Tel.: + 39-02-5800-2342; fax: +39-02-5801-1194.

E-mail address: aparolari@cardiologicomonzino.it (A. Parolari).

1010-7940/00/$ - see front matter
PII: S1010-7940(00)00552-2

which was induced by the administration of sodium thiopental (3 mg/kg), fentanyl (0.75 μg/kg), succinylcholine (1 mg/kg), diazepam (10 mg) and pancuronium bromide (0.1 mg/kg). After endotracheal intubation, patients were ventilated to normocapnia with an oxygen and air mixture. Boluses of fentanyl (with or without droperidol), diazepam and pancuronium bromide were given when necessary. Cefuroxime (2 g) was given intravenously for infection prophylaxis. A radial artery catheter and a flow-directed pulmonary artery catheter were inserted for hemodynamic measurements. The extracorporeal circuit consisted of a roller pump (CAPS HLM; Stockert Instruments, Munich, Germany) or a centrifugal pump (Biomedicus BioPump; Medtronic, Milan, Italy), hollow fiber oxygenator with integrated heat exchanger, arterial filter, cardiotomy reservoir and polyvinyl tubing system. In all cases, an 'open' system was used for perfusion.

The type of pump was chosen based on a consensus between the surgeon and anesthesiologist, with preference given to the centrifugal pump for CPB times which were expected to be longer (>100 min).

No heparin bonding was used in the perfusion tubing or oxygenator. The extracorporeal circuit was primed with 1500 ml electrolyte solution and 5000 IU bovine lung heparin (Liquemin; Roche, Italy).

After systemic heparinization (300 U/kg), CPB was initiated with cannulas placed in the ascending aorta and right atrium. The activated clotting time was kept at ≥400 s with additional heparin.

The pump flow was non-pulsatile in all operations. The flow rate was maintained at 2.4 l/min per m^2 during cooling and rewarming phases, and at 2.0 l/min per m^2 during stable hypothermia. The mean arterial pressure (MAP) during CPB was maintained between 60 and 90 mmHg, with CPB flows set as previously described, and vasoactive drugs were used to maintain the MAP in the desired range: if the MAP increased above the desired range, and was unresponsive to fentanyl or diazepam, sodium nitroporusside was started, but if the MAP fell below the desired range, norepinephrine, boluses or continuous infusion were added. Patients were cooled to 28–30°C. CPB flows and pressures were downloaded from the monitor and recorded every 5 min during perfusion. Any significant modification of the perfusion pattern during 5 min time intervals was also recorded by the perfusionist.

For myocardial protection, patients received a first dose (1000 cc) of cool (4°C) antegrade and retrograde high-potassium cold crystalloid cardioplegia (St. Thomas Hospital Cardioplegic solution containing 110 mmol/l NaCl, 16 mmol/l KCl, 16 mmol/l $MgCl_2$, 1.2 mmol/l $CaCl_2$ and 10 mmol/l $NaHCO_3$) just after aortic cross-clamping, which was repeated (250 ml retrograde) at every 20 min of the aortic cross-clamp time. Disturbances in the acid–base balance were appropriately treated, and the acid–base equilibrium was maintained by the alpha-STAT method. The hematocrit during CPB was maintained at 18–25%.

After termination of CPB, heparin was antagonized with protamine sulfate at a 1:1 ratio (3 mg/kg). If necessary, inotropic support was given when patients were weaned from CPB. Autologous blood and residual volume from the extracorporeal circuit were infused into the patient when volume supplementation was necessary.

Table 1
Preoperative variables of the study population[a]

Age at intervention (years)	64 (57–70)
Preoperative weight (kg)	76 (64–80)
Body surface area (m^2)	1.8 (1.7–1.9)
Male sex	2885/4000 (72)
History of hypertension	2142/4000 (54)
History of smoking	1610/4000 (40)
Previous myocardial infarction	1685/4000 (42)
Previous cardiac surgery	288/4000 (7.2)
Previous vascular surgery	152/4000 (3.8)
Insulin-dependent diabetes mellitus	103/4000 (2.6)
Peripheral vascular disease	414/4000 (10)
History of asthma	66/4000 (1.7)
History of COPD	344/4000 (8.6)
History of heart failure	535/4000 (13)
Previous TIA	271/4000 (6.8)
Previous RIND	43/4000 (1.1)
Previous stroke	147/4000 (3.7)
Previous neurological events	448/4000 (11)
Blood hematocrit (%)	39 (36–42)
Blood creatinine level (mg/dl)	1.1 (9–1.2)
Blood creatinine level (>2 mg/dl)	57/4000 (1.4)
Sinus rhythm at preoperative EKG	3380/4000 (85)

[a] Numbers in parentheses represent either percentage values or 25th and 75th percentiles.

Table 2
Operative variables of the study population[a]

Type of surgery	
CABG	2704/4000 (68)
AVR	477/4000 (12)
MVR	416/4000 (10)
DVR	220/4000 (5.5)
CABG + VR	183/4000 (4.5)
Use of centrifugal pump for CPB	2213/4000 (55)
Aortic cross-clamp time (min)	79 (61–101)
CPB time (min)	109 (88–136)
Need to perform a circulatory arrest (>5 min)	17/4000 (0.4)
CPB flow during the cooling phase (l/min per m^2)	2.3 (2.1–2.4)
Blood pressure during the cooling phase (mmHg)	70 (60–80)
CPB flow during the stable hypothermia phase (l/min per m^2)	2 (1.8–2.2)
Blood pressure during the stable hypothermia phase (mmHg)	75 (65–85)
CPB flow during the rewarming phase (l/min per m^2)	2.3 (2.2–2.4)
Blood pressure during the rewarming phase (mmHg)	70 (65–80)
Minimum esophageal temperature reached (°C)	29.2 (27.6–30.0)
Minimum rectal temperature reached (°C)	30.6 (29.6–31.5)
CPB flow during the entire bypass time (l/min per m^2)	2.2 (2.1–2.3)
Blood pressure during the entire bypass time (mmHg)	73 (67–79)

[a] Numbers in parentheses represent either percentage values or 25th and 75th percentiles.

Table 3
Preoperative variables of the study population by the type of pump[a]

Variable	Centrifugal pump	Roller pump	*P*
Age at intervention (years)	64 (57–70)	64 (56–70)	0.25
Preoperative weight (kg)	72 (64–80)	71 (64–80)	0.086
Body surface area (m^2)	1.8 (1.7–1.9)	1.8 (1.7–1.9)	0.25
Male sex[b]	73 (1614/2213)	71 (1271/1787)	0.21
History of hypertension[b]	53 (1176/2213)	54 (966/1787)	0.58
History of smoking[b]	41 (915/2213)	39 (695/1787)	0.12
Previous myocardial infarction[b]	45 (984/2213)	39 (701/1787)	< 0.001
Previous cardiac surgery[b]	8.6 (190/2213)	5.5 (98/1787)	< 0.001
Previous vascular surgery[b]	3.7 (81/2213)	4.0 (71/1787)	0.66
Insulin-dependent diabetes mellitus[b]	3.1 (68/2213)	2.0 (35/1787)	0.035
Peripheral vascular disease[b]	11 (239/2213)	9.8 (175/1787)	0.32
History of asthma[b]	1.7 (37/2213)	1.6 (29/1787)	0.99
History of COPD[b]	8.2 (181/2213)	9.1 (163/1787)	0.31
History of heart failure[b]	12 (275/2213)	15 (260/1787)	0.056
Previous TIA[b]	7.7 (170/2213)	5.7 (101/1787)	0.013
Previous RIND[b]	1.1 (25/2213)	1.0 (18/1787)	0.82
Previous stroke[b]	4.2 (94/2213)	3.0 (53/1787)	0.040
Previous neurological events[b]	13 (285/2213)	9.1 (163/1787)	< 0.001
Blood hematocrit (%)	40 (36–43)	39 (35–42)	< 0.001
Blood creatinine level (mg/dl)	1.1 (0.9–1.2)	1.1 (0.9–1.2)	0.23
Blood creatinine level (>2 mg/dl)[b]	1.5 (33/2213)	1.3 (24/1787)	0.78
Sinus rhythm at preoperative EKG[b]	84 (1859/2213)	85 (1521/1787)	0.35

[a] Centrifugal vs. roller.
[b] Figures represent either percentage values followed by the proportion in parentheses or median followed by 25th and 75th percentile in parentheses.

After surgery, patients were admitted to the intensive care unit (ICU) and treated according to a standardized protocol. The MAP was kept at 70–90 mmHg, heart rate at 70–90 beats/min, and the cardiac index was maintained at greater than 2.0 l/min per m^2. Inotropic support was administered when necessary. Patients were ventilated to normocapnia, and an arterial oxygen tension of 80 mmHg with continuous positive-pressure ventilation until extubation was maintained according to the ICU regimen. Basic fluid administration consisted of 0.9% NaCl and polygelatine. Packed erythrocytes were infused when the hematocrit was <18% during CPB and <24% in the ICU. When their cardio-

Table 4
Operative variables of the study population by the type of pump[a]

Variable	Centrifugal pump	Roller pump	*P*
Type of surgery			
CABG[b]	68 (1513/2213)	67 (1191/1787)	0.30
AVR[b]	12 (264/2213)	12 (213/1787)	
MVR[b]	11 (232/2213)	10 (184/1787)	
DVR[b]	5 (107/2213)	6 (113/1787)	
CABG + VR[b]	4 (97/2213)	5 (86/1787)	
Aortic cross-clamp time (min)	81 (62–1049)	76 (60–98)	< 0.001
CPB time (min)	112 (90–140)	106 (85–131)	< 0.001
Need to perform a circulatory arrest (>5 min)[b]	0.7 (16/2213)	0.4 (7/1787)	0.24
CPB flow during the cooling phase (l/min)	2.3 (2.2–2.4)	2.3 (2.2–2.4)	< 0.001
Blood pressure during the cooling phase (mmHg)	75 (65–80)	70 (60–75)	< 0.001
CPB flow during the stable hypothermia phase (l/min per m^2)	2.0 (1.8–2.1)	2.0 (1.8–2.2)	< 0.001
Blood pressure during the stable hypothermia phase (mmHg)	80 (70–85)	70 (60–80)	< 0.001
CPB flow during the rewarming phase (l/min per m^2)	2.3 (2.2–2.4)	2.3 (2.2–2.5)	< 0.001
Blood pressure during the rewarming phase (mmHg)	75 (65–80)	70 (65–75)	< 0.001
Minimum esophageal temperature reached (°C)	29.5 (28.5–30.1)	28.3 (27.1–29.8)	< 0.001
Minimum rectal temperature reached (°C)	30.8 (30.0–31.6)	30.4 (29.3–31.5)	< 0.001
CPB flow during the entire bypass time (l/min per m^2)	2.2 (2.0–2.3)	2.2 (2.1–2.4)	< 0.001
Blood pressure during the entire bypass time (mmHg)	75 (69–82)	70 (63–77)	< 0.001

[a] Centrifugal vs. roller.
[b] Figures represent either percentage values followed by the proportion in parentheses or median followed by 25th and 75th percentile in parentheses.

Table 5
Significant or borderline univariate risk factors for in-hospital death

Variable	In-hospital deaths vs. hospital survivors	*P* value
Age at intervention (years)	67 (61–71) vs. 64 (57–70)	0.026
Preoperative weight (kg)	65 (55–76) vs. 72 (64–80)	< 0.001
Body surface area (m^2)	1.7 (1.6–1.9) vs. 1.8 (1.7–1.9)	0.001
Male sex[a]	61 (54/88) vs. 72 (2831/3912)	0.031
Previous cardiac surgery[a]	22 (19/88) vs. 6.9 (269/3912)	< 0.001
History of COPD[a]	17 (15/88) vs. 8.4 (329/3912)	0.008
History of heart failure	24 (21/88) vs. 13 (514/3912)	0.006
Previous RIND[a]	3.4 (3/88) vs. 1.0 (40/3912)	0.1
Previous stroke[a]	8.0 (7/88) vs. 3.6 (140/3912)	0.061
Blood hematocrit (%)	36 (33–40) vs. 39 (36–42)	< 0.001
Blood creatinine level (mg/dl)	1.1 (1.0–1.5) vs. 1.1 (0.9–1.2)	0.077
Blood creatinine level (>2 mg/dl)[a]	6.8 (6/88) vs. 1.3 (51/3912)	< 0.001
Sinus rhythm at preoperative EKG[a]	74 (65/88) vs. 85 (3315/3912)	0.008
Aortic cross-clamp time (min)	95 (74–131) vs. 78 (61–100)	< 0.001
CPB time (min)	149 (115–202) vs. 109 (87–135)	< 0.001
CABG operation[a]	58 (51/88) vs. 68 (2653/3912)	0.066
VR + CABG operation[a]	13 (11/88) vs. 4.4 (172/3912)	< 0.001
Need to perform a circulatory arrest >5 min[a]	2.3 (2/88) vs. 0.4 (15/3912)	0.062
CPB flow during the cooling phase (l/min per m^2)	2.3 (2.1–2.4) vs. 2.3 (2.2–2.4)	< 0.001
CPB flow during the stable hypothermia phase (l/min per m^2)	2 (1.8–2.3) vs. 2 (1.8–2.2)	0.18
Blood pressure during the stable hypothermia phase (mmHg)	75 (60–80) vs. 75 (65–85)	0.17
CPB flow during the rewarming phase (l/min per m^2)	2.3 (2.2–2.5) vs. 2.3 (2.1–2.5)	0.010
Minimum esophageal temperature reached (°C)	28.4 (27.0–30.0) vs. 29.2 (27.6–30.0)	0.001
Minimum rectal temperature reached (°C)	30.2 (28.7–31.1) vs. 30.6 (29.6–31.5)	0.021

[a] Figures represent changes percentage values followed by the proportion in parentheses as per Tables 3 + 4.

respiratory condition had stabilized, patients were transported to the ward for further recovery.

2.2. Statistical analysis

The data are presented as medians (25 and 75% percentiles in brackets) for continuous variables or percentages for categorical variables. A commercial statistical package (SPSS for Windows Version 8.0; SPSS, Inc., Chicago, IL) was used for data analysis.

Thirty-seven preoperative and operative variables, including the type of pump employed for CPB (roller vs. centrifugal; Tables 1 and 2) were assessed for their possible effect on the occurrence of the following outcomes, which were defined as follows:

In-hospital mortality: any death occurring within 30 days after surgery, or anytime before discharge of the patient from the hospital;

Permanent neurological deficit: a central neurological deficit persisting >72 h;

Coma: unresponsiveness >24 h in the absence of sedation.

All continuous variables were first tested individually (univariate sense) with the non-parametric Mann–Whitney test, while categorical variables were explored by the Chi-square (Yates' continuity correction) or the Fisher's exact test when indicated.

The factors which were at least marginally significant ($P \leq 0.2$) by univariate analysis were included into a multivariable forward stepwise logistic regression model. The multivariate odds ratio (OR) for each independent variable in the final regression models and 95% confidence intervals were also computed. The *P* value for entry of a covariate into the model was set at a significance level 0.05, while the *P* value for the removal of a covariate was fixed at the 0.1 significance level. Every multivariable model was tested for reliability with the Hosmer–Lemeshow statistic [11].

3. Results

3.1. Patient population

The preoperative and operative clinical features of the patient population are reported in Tables 1 and 2, respectively. Briefly, the median age was 65, 72% of the patients were male, 3.7% had had a previous stroke, 7.2% were

Table 6
Results of multivariate logistic regression for in-hospital death[a]

Variable	OR	95% CI	*P* value
CPB time (min)	1.015	1.011–1.394	0.0001
Previous cardiac surgery	1.7	1.2–2.3	0.0026
Blood creatinine level >2 mg/dl	2.0	1.1–3.6	0.0189
Blood hematocrit (%)	0.94	0.88–0.99	0.0215

[a] Hosmer–Lemeshow goodness-of-fit-test, $\chi^2(8) = 7.01$; $P = 0.54$.

Table 7
Interaction among in-hospital mortality, neurological outcomes, and type of pump

	In-hospital mortality			Total	*P*
	Yes	No	%		
All patients ($n = 4000$)					
Perioperative coma					
Yes	24	28	46	52	
No	64	3884	1.6	3948	
Total	88	3912		4000	< 0.001
Perioperative permanent neurological deficit					
Yes	14	67	17	81	
No	74	3845	2.0	3919	
Total	88	3912		4000	< 0.001
Patients operated with centrifugal pump use ($n = 2213$)					
Perioperative coma					
Yes	10	10	50	20	
No	40	2153	1.9	2193	
Total	50	2163		2213	< 0.001
Perioperative permanent neurological deficit					
Yes	7	27	21	34	
No	43	2136	2.0	2179	
Total	50	2163		2213	< 0.001
Patients operated with roller pump use ($n = 1787$)					
Perioperative coma					
Yes	14	18	44	32	
No	24	1731	1.4	1755	
Total	38	1749		1787	< 0.001
Perioperative permanent neurological deficit					
Yes	7	40	1.5	47	
No	31	1709	1.8	1740	
Total	38	1749		1787	< 0.001

redos, 13% had a history of heart failure, 68% underwent coronary artery bypass grafting, 55% underwent surgery with the use of a centrifugal pump, and the median CPB time was 110 min.

The clinical variables of patients who underwent surgery using centrifugal or roller pumps are reported in Tables 3 and 4. Regarding preoperative variables, the two groups of patients were similar in age, body surface area, gender, history of hypertension, preoperative pulmonary, and renal status; on the other hand, patients who underwent surgery with the use of a centrifugal pump had a higher incidence of previous myocardial infarction, insulin-dependent diabetes mellitus, were more frequently redos, and had a higher incidence of previous transitory ischemic attack (TIAs), strokes, and overall neurological events. The analysis of the operative variables showed similar frequencies in the different types of surgery, as well as in the need to perform a circulatory arrest, while aortic cross-clamp and CPB times were, as expected, longer in cases using a centrifugal pump. Finally, there were statistically significant differences in perfusion pressures, flows and temperatures between roller and centrifugal pumps: pump flows were slightly lower in cases of centrifugal pump use, while pressures and temperatures were slightly higher; however, in no case did the differences between the two groups in CPB-related variables exceed a 10% variation, and this was reported as less than 5% in most of the comparisons.

3.2. In-hospital mortality

The overall in-hospital mortality rate of this series of patients was 2.2% (88/4000); there was no difference between hospital mortalities based on the type of pump, those being 2.3 (50/2213) and 2.1% (38/1787) for patients who were operated on using centrifugal and roller pumps, respectively ($P = 0.860$). The univarate risk factors for in-hospital death are reported in Table 5; and the multivariate risk factors for in-hospital death were longer CPB times, previous cardiac surgery, blood creatinine levels > 2 mg/dl, and lower blood hematocrit levels (Table 6).

The interactions among in-hospital mortality, neurologi-

Table 8
Significant or borderline univariate risk factors for perioperative permanent neurological deficit

Variable	Perioperative neurological deficit vs. no perioperative neurological deficit	*P* value
Age at intervention (years)	67 (63–72) vs. 64 (57–70)	0.002
Previous vascular surgery[a]	8.6 (7/81) vs. 3.7 (145/3919)	0.045
Peripheral vascular disease[a]	17 (14/81) vs. 10 (400/3919)	0.059
Previous TIA[a]	20 (16/81) vs. 6.5 (255/3919)	< 0.001
Blood hematocrit (%)	38 (35–40) vs. 39 (36–42)	0.020
Blood creatinine level (mg/dl)	1.2 (1.0–1.4) vs. 1.1 (0.9–1.2)	0.002
Blood creatinine level >2 mg/dl[a]	4.9 (4/81) vs. 1.4 (53/3919)	0.026
Sinus rhythm at preoperative EKG[a]	75 (61/81) vs. 85 (3319/3919)	0.031
Use of centrifugal pump for CPB[a]	42 (34/81) vs. 56 (2179/3919)	0.020
Aortic cross-clamp time (min)	85 (67–105) vs. 79 (61–101)	0.070
CPB time (min)	122 (91–159) vs. 109 (88–135)	0.009
Need to perform a circulatory arrest >5 min[a]	2.5 (2/81) vs. 0.4 (15/3919)	0.002
Minimum esophageal temperature reached (°C)	29.0 (27.2–29.8) vs. 29.2 (27.6–30.0)	0.054
Minimum rectal temperature reached (°C)	30.4 (28.9–31.1) vs. 30.6 (29.6–31.6)	0.005

[a] Figures represent either percentage values followed by the proportion in parentheses or median followed by 25th and 75th percentiles in parentheses.

Table 9
Results of multivariate logistic regression for perioperative permanent neurological deficit[a]

Variable	OR	95% CI	*P* value
CPB time (min)	1.007	1.004–1.010	0.0001
Previous TIA	2.5	1.5–4.4	0.0067
Age at intervention (years)	1.038	1.014–1.062	0.0116
Use of centrifugal pump for CPB	0.57	0.38–0.87	0.0363

[a] Hosmer–Lemeshow goodness-of-fit-test, $\chi^2(8) = 8.86$; $P = 0.35$.

cal outcomes and pump type are reported in Table 7. Patients who showed a permanent neurological deficit or coma had higher in-hospital mortality rates compared with patients free from these complications; similar results were obtained from separate analysis of patients operated with centrifugal or roller pumps.

3.3. Analysis of the risk factors for the occurrence of perioperative permanent neurological deficit

The significant or marginally significant univariate risk factors for perioperative permanent neurological deficit are reported in Table 8. Patients who underwent surgery with the use of a centrifugal pump had a permanent neurological deficit rate of 1.5% (34/2213), while the incidence of this complication in patients who were operated with a roller pump was 2.6% (47/1787; $P = 0.020$). Multivariable logistic regression analysis identified longer CPB times, previous TIAs and increasing age as multivariate risk factors for perioperative permanent neurological deficit, while the use of a centrifugal pump for CPB emerged as a protective factor (Table 9).

3.4. Analysis of the risk factors for the occurrence of perioperative coma

The significant or marginally significant univariate risk factors for perioperative coma are reported in Table 10. Regarding the type of pump used for perfusion, patients who underwent surgery with a centrifugal pump had a perioperative coma rate of 0.9% (20/2213), while the incidence of coma in patients who were operated using a roller pump was 1.8% (32/1787; $P = 0.020$). Multivariable logistic regression analysis identified longer CPB times, previous vascular surgery and increasing age as independent risk factors for the occurrence of perioperative coma, while centrifugal pump use resulted as protective (Table 11).

4. Discussion

The continuous improvement of techniques in adult cardiac surgery has substantially reduced the morbidity and mortality in cardiac operations requiring CPB. Despite these advances, however, adverse neurological and neurobehavioral outcomes continue to occur, at perhaps an increased frequency, due to the progressive aging of the population of patients undergoing cardiac surgery [1,2].

To date, several studies assessed the effect of CPB-related variables on neurological outcomes in adult patients undergoing cardiac surgery; in particular, it could be demonstrated that longer CPB times [4,5] and severity of ascending aorta atherosclerosis [4,8] were strong predictors

Table 10
Significant or borderline univariate risk factors for perioperative coma

Variable	Perioperative coma vs. no perioperative coma	*P* value
Age at intervention (years)	69 (64–72) vs. 64 (57–70)	0.001
Preoperative weight (kg)	68 (60–72) vs. 72 (64–80)	0.001
Body surface area (m^2)	1.7 (1.6–1.8) vs. 1.8 (1.7–1.9)	0.001
Previous cardiac surgery[a]	15 (8/52) vs. 7.1 (280/3948)	0.043
Previous vascular surgery[a]	13 (7/52) vs. 3.7 (145/3948)	< 0.001
Peripheral vascular disease[a]	21 (11/52) vs. 10 (403/3948)	0.019
Previous RIND[a]	5.8 (3/52) vs. 1.0 (43/3948)	0.009
Previous stroke[a]	12 (6/52) vs. 3.6 (141/3948)	0.008
Blood hematocrit (%)	35 (33–39) vs. 39 (36–42)	< 0.001
Blood creatinine level (mg/dl)	1.2 (1.0–1.5) vs. 1.1 (0.9–1.2)	< 0.001
Sinus rhythm at preoperative EKG[a]	63 (33/52) vs. 85 (3347/3948)	< 0.001
Use of centrifugal pump for CPB[a]	38 (20/52) vs. 56 (2193/3948)	0.020
Aortic cross-clamp time (min)	91 (76–126) vs. 79 (61–100)	0.005
CPB time (min)	148 (111–181) vs. 109 (88–135)	< 0.001
Need to perform a circulatory arrest >5 min[a]	5.8 (3/52) vs. 0.4 (14/3948)	0.013
Blood pressure during the stable hypothermia phase (mmHg)	70 (60–80) vs. 75 (65–85)	0.030
Blood pressure during the rewarming phase (mmHg)	70 (65–75) vs. 70 (65–80)	0.024
Minimum esophageal temperature reached (°C)	28.2 (27.0–29.3) vs. 29.2 (27.6–30.0)	0.002
Minimum rectal temperature reached (°C)	30.0 (28.4–31.1) vs. 30.6 (29.6–31.5)	0.005

[a] Figures outside either parentheses represent percentage values or median followed by 25th and 75th percentiles in parentheses.

Table 11
Results of multivariate logistic regression for perioperative coma[a]

Variable	OR	95% CI	*P* value
CPB time (min)	1.012	1.009–1.014	< 0.0001
Previous vascular surgery	4.8	2.5–9.0	0.0007
Age at intervention (years)	1.054	1.026–1.083	0.0075
Use of centrifugal pump for CPB	0.46	0.29–0.74	0.0246

[a] Hosmer–Lemeshow goodness-of-fit-test, $\chi^2(8) = 3.60$; $P = 0.89$.

of perioperative neurological complications, while lack of arterial line filtration [9,12] and pH-stat acid–base management [10] could also increase the occurrence of postoperative central nervous system dysfunction. On the other hand, the possible effects of other CPB variables are still being debated, and the roles of temperature management (normothermic vs. moderately hypothermic perfusion), mean arterial pressure levels during CPB and type of perfusion (pulsatile vs. non-pulsatile) in affecting neurological complication rates have not yet been completely defined [13].

Centrifugal pumps have been widely used as the main pump in adult cardiac surgery, and are considered by some authors to be superior to the traditionally used roller pumps because of less blood trauma [14], reduced activation of the coagulation cascade [15] and improved biocompatibility [16], even if some of the studies could not document any significant benefits in terms of hemolysis [17], platelet damage [18] or immune response [19]; in addition, some recent evidence could document an increased inflammatory response to CPB in cases using centrifugal pumps [20,21].

There is less information, however, on the effect of the use of this kind of pump on clinical endpoints, and the effects on neurological function are not well established yet; even if centrifugal pumps have been shown to generate fewer microemboli than roller pumps [22], it was recently demonstrated that, for CPB times of less than 90 min, centrifugal pumps did not decrease serum S100β release, a marker for cerebral injury, compared with roller pumps [23]. In addition, only one paper, by Klein and colleagues, has previously evaluated the effect of centrifugal and roller pumps used for CPB on many different clinical outcomes, documenting a reduced rate of neurological complications when a centrifugal pump was used for perfusion; but no additional information was given about the criteria used to define neurological complications in this paper [24].

The aim of our study was then to retrospectively review the data concerning adult patients who underwent coronary and/or valve surgery at our hospital during a 5.5-year period (1994–June 1999); during that period, in fact, both types of pump (roller and centrifugal) were used at our hospital at the same time by the same team of surgeons, anesthesiologists and perfusionists. Our study could show that factors related both to the preoperative clinical status of the patients and to operative and CPB features can affect the occurrence of major neurological complications; age at intervention, previous vascular surgery, previous neurological episodes, as well as longer CPB times were risk factors for adverse neurological outcomes of adult cardiac surgery patients, as previously described [13].

In addition, our study documented that the use of a centrifugal pump can reduce the rates of the two most feared neurological complications of routine adult cardiac surgery performed with the use of CPB; univariate and multivariate analyses documented its protective effect, for the occurrence of both perioperative permanent neurological deficit and perioperative coma, reducing the risk reduction for the considered events by approximately half (multivariable ORs of 0.57 and 0.46 for perioperative permanent neurological deficit and perioperative coma, respectively).

Interestingly, the protective effect of centrifugal pump use could be documented even if there was a clear selection bias between the two pump types in our patient population, and centrifugal pumps were preferred, as previously stated, for cases with longer perfusion times. Also, the subgroup analysis comparing preoperative and operative variables by the type of pump could confirm that patients operated with centrifugal pumps, aside from the expected longer aortic cross-clamp and CPB times, also had an increased risk profile for the considered events, being more frequently redos, insulin-dependent diabetics, and having a higher rate of pre-existing neurological events; in fact, all of these three factors were previously documented as risk factors for unfavorable neurological outcome [2].

The hypothesis to explain the protective effect of the centrifugal pumps used for CPB is, that with centrifugal pumps, the embolic load to the brain is lower [22], as was previously demonstrated with ultrasonic microbubble detection in the arterial CPB line [25].

On the other hand, the potential neurological benefit of the use of a centrifugal pump for perfusion was not paralleled by a decrease in in-hospital mortality; this finding has no clear explanation to us, and further investigations will be needed to clarify this point.

In conclusion, this study, with the limits of a retrospective, non-randomized study, suggests that centrifugal pump use during routine adult cardiac surgery reduced perioperative permanent neurological deficit and coma rates. Prospective, multi-institutional, randomized studies will be needed to better define the possible protective effects of centrifugal pumps on neurological outcomes of adult cardiac surgery.

References

[1] Cosgrove DM, Loop FD, Lytle BW, Baillot R, Gill CC, Golding LA, Taylor PC, Goormastic M. Primary myocardial revascularization. Trends in surgical mortality. J Thorac Cardiovasc Surg 1984;88:673–684.

[2] Tuman KJ, McCarthy RJ, Najafi H, Ivankovich AD. Differential effects of advanced age on neurologic and cardiac risks of coronary artery operations. J Thorac Cardiovasc Surg 1992;104:1510–1517.

[3] McLean RF, Wong BI, Naylor CD, Snow WG, Harrington EM, Gawel M, Fremes SE. Cardiopulmonary bypass, temperature, and

central nervous system dysfunction. Circulation 1994;90(Suppl II):II250–II255.

[4] Cernaianu AC, Vassilidze TV, Flum DR, Maurer M, Cilley Jr JH, Grosso MA, DelRossi AJ. Predictors of stroke after cardiac surgery. J Card Surg 1995;10:334–339.

[5] McKhann GM, Goldsborough MA, Borowicz Jr LM, Mellits ED, Brookmeyer R, Quaskey SA, Baumgartner WA, Cameron DE, Stuart RS, Gardner TJ. Predictors of stroke risk in coronary artery bypass patients. Ann Thorac Surg 1997;63:516–521.

[6] Mora CT, Henson MB, Weintraub WS, Murkin JM, Martin TD, Craver JM, Gott JP, Guyton RA. The effect of temperature management during cardiopulmonary bypass on neurologic and neuropsychologic outcomes in patients undergoing coronary revascularization. J Thorac Cardiovasc Surg 1996;112:514–522.

[7] Gold JP, Charlson ME, Williams-Russo P, Szatrowski TP, Peterson JC, Pirraglia PA, Hartmann GS, Yao FSF, Hollenberg JP, Barbut D, Hayes JG, Thomas SJ, Purcell MH, Mattis S, Gorkin L, Post M, Krieger K, Isom OW. Improvement of outcomes after coronary artery bypass. A randomized trial comparing intraoperative high versus low mean arterial pressure. J Thorac Cardiovasc Surg 1995;110:1302–1314.

[8] Roach GW, Kanchuger M, Mangano CM, Newman M, Nussmeier N, Wolman R, Aggarwal A, Marschall K, Graham SH, Ley C. Adverse cerebral outcomes after coronary bypass surgery. Multicenter study of Perioperative Ischemia Research Group and the Ischemia Research and Education Foundation Investigators. New Engl J Med 1996;335:1857–1863.

[9] Pugsley W, Klinger L, Paschalis C, Treasure T, Harrison H, Newman S. The impact of microemboli during cardiopulmonary bypass on neuropsychological functioning. Stroke 1994;25:1393–1399.

[10] Murkin JM. The role of CPB management in neurobehavioral outcomes after cardiac surgery. Ann Thorac Surg 1995;59:1308–1311.

[11] Hosmer Jr DW, Lemeshow S. Assessing the fit of the model. In: Hosmer Jr DW, Lemeshow S, editors. Applied logistic regression, New York: Wiley, 1989. pp. 135–175.

[12] Blauth CI, Arnold JV, Schulenberg WE, McCartney AC, Taylor KM. Cerebral microembolism during cardiopulmonary bypass. Retinal microvascular studies in vivo with fluorescein angiography. J Thorac Cardiovasc Surg 1988;95:668–676.

[13] Newman MF. Strategies to protect the brain during cardiac surgery. Presented at the Outcomes '99 Meeting, Key West, FL, May 27–29, 1999.

[14] Moen O, Fosse E, Braten J, Andersson C, Hogasen K, Mollnes TE, Venge P, Kierulf P. Differences in blood activation related to roller/centrifugal pumps and heparin-coated/uncoated surfaces in a cardiopulmonary bypass model circuit. Perfusion 1996;11:113–123.

[15] Steinbrueckner BE, Steigerwald U, Keller F, Neukam K, Elert O, Babin-Ebell J. Centrifugal and roller pumps – are there differences in coagulation and fibrinolysis during and after cardiopulmonary bypass? Heart Vessels 1995;10:46–53.

[16] Moen O, Fosse E, Dregelid E, Brockmeier V, Andersson C, Hogasen K, Venge P, Mollnes TE, Kierulf P. Centrifugal pump and heparin coating improves cardiopulmonary bypass biocompatibility. Ann Thorac Surg 1996;62:1134–1140.

[17] Hansbro SD, Sharpe DA, Catchpole R, Welsh KR, Munsch CM, McGoldrick JP, Kay PH. Haemolysis during cardiopulmonary bypass: an in vivo comparison of standard roller pumps, non-occlusive roller pumps and centrifugal pumps. Perfusion 1999;14:3–10.

[18] Misoph M, Babin-Ebell J, Schwender S. A comparative evaluation of the effect of pump type and heparin-coated surfaces on platelets during cardiopulmonary bypass. Thorac Cardiovasc Surg 1997;45:302–306.

[19] Perttila J, Salo M, Peltola O. Comparison of the effects of centrifugal versus roller pump on the immune response in open-heart surgery. Perfusion 1995;10:249–256.

[20] Ashraf S, Butler J, Tian Y, Cowan D, Lintin S, Saunders NR, Watterson KG, Martin PG. Inflammatory mediators in adults undergoing cardiopulmonary bypass: comparison of centrifugal and roller pumps. Ann Thorac Surg 1998;65:480–484.

[21] Baufreton C, Intrator L, Jansen PG, Le Besnerais VHP, Vonk A, Farcet JP, Wildevuur CR, Loisance DY. Inflammatory response to cardiopulmonary bypass using roller or centrifugal pumps. Ann Thorac Surg 1999;67:972–977.

[22] Clark RE, Goldstein AH, Pacella JJ, Walters RA, Moeller FW, Cattivera GR, Davis S, Magovern Sr GJ. Small, low-cost implantable centrifugal pump for short-term circulatory assistance. Ann Thorac Surg 1996;61:452–456.

[23] Ashraf S, Bhattacharya K, Zacharias S, Kaul P, Kay PH, Watterson KG. Serum S100beta release after coronary artery bypass grafting: roller versus centrifugal pump. Ann Thorac Surg 1998;66:1958–1962.

[24] Klein M, Dauben HP, Schulte HD, Gams E. Centrifugal pumping during routine open heart surgery improves clinical outcome. Artif Organs 1998;22:326–336.

[25] Wheeldon DR, Bethune DW, Gill RD. Vortex pumping for routine cardiac surgery: a comparative study. Perfusion 1990;5:135–143.