Extracorporeal Resuscitation of Cardiac Arrest

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Abstract. **Objective:** Extracorporeal support of heart and lung function (venoarterial perfusion) during cardiac arrest (ECPR) has been advocated as a means of improving survival following cardiac arrest. The authors retrospectively reviewed their institution's seven-year experience with this intervention. **Methods:** Emergency department patients and inpatients in cardiac arrest or immediately postarrest were considered candidates. ECPR was instituted using venoarterial bypass and was continued until patients regained sufficient cardiopulmonary function to allow weaning from the device or until their condition was deemed irrecoverable. **Results:** ECPR was attempted in 25 patients and successfully instituted in 21. Four patients (16%) were converted from ECPR to ventricular assist devices, two of whom survived and await transplantation. Seven additional patients were discharged from the hospital, resulting in an overall survival of 36%. Because none of the children treated survived, there was a trend toward higher age among survivors (survivors 40 $\pm$ 14 yr, nonsurvivors 33 $\pm$ 15 yr, p = 0.29). The duration of conventional CPR was shorter among survivors (survivors 21 $\pm$ 16 min, nonsurvivors 43 $\pm$ 32 min, p = 0.04), as was the duration of extracorporeal support (survivors 44 $\pm$ 21 hr, nonsurvivors 87 $\pm$ 96 hr, p = 0.18). Survival was seen only in patients whose conditions were amenable to a definitive therapeutic intervention, particularly cardiac arrest due to respiratory or pulmonary embolic disease. While four of the five patients treated in the ED were successfully supported, none survived to discharge. **Conclusion:** In select patients with reversible disease, extracorporeal CPR can be used to successfully treat cardiac arrest. Further investigation into its most appropriate application is warranted. **Key words:** extracorporeal cardiopulmonary resuscitation; CPR; venoarterial perfusion; cardiac arrest; survival. ACADEMIC EMERGENCY MEDICINE 1999; 6:700–707

DESPITE decades of investigation into its treatment, cardiac arrest remains one of the most unyielding clinical phenomena encountered in daily medical practice. Discharge from the hospital with meaningful neurologic function occurs in fewer than 5% of patients sustaining cardiac arrest outside of a hospital.[1] The prognosis of adults who lose their vital signs while in a hospital is nearly as poor, with only 5% to 15% surviving in both medical and surgical series.[2–5] Infants and children requiring cardiopulmonary resuscitation (CPR) can expect similar outcomes: survival among children has been estimated at 20%,[6] and among neonates, 6%.[7]

In many patients, cardiac arrest represents the final event in the course of a chronic, progressive condition. However, other conditions such as acute myocardial infarction, pulmonary embolic disease, or acute respiratory insufficiency may produce cardiac arrest in patients who might otherwise expect years of productive survival. Obstacles to improved outcome in such individuals include the frequent inability to rapidly restore perfusion and the limited ability to generate adequate native oxygen delivery in the postarrest period. The clinical results are occasional "successful" resuscitations in which the patients often die hours to days later in the intensive care unit (ICU) of neurologic or other complications.

Given the relative infrequency of the return of spontaneous circulation (ROSC), and the incomplete support native postarrest cardiopulmonary function provides to injured organs, some authors advocate external, or extracorporeal, means of providing oxygen delivery during and after cardiac arrest. Extensive animal data[8] and preliminary reports of clinical experience[9–11] suggest that extracorporeal CPR (ECPR) might be a superior means of resuscitating some victims of cardiac arrest.

Our institution began providing ECPR to select patients in 1991. Our earliest experience with the ECPR protocol described below has been reported elsewhere.[12] The ECPR service evolved as an ex-

tension of our extracorporeal membrane oxygenation (ECMO) program. The ECMO team consists of attending physicians, resident-fellows, and clinical specialists who provide extracorporeal support for neonates, infants, and adults with severe respiratory failure. This paper reviews our seven-year experience with the use of extracorporeal support for the treatment of cardiopulmonary arrest.

METHODS

Study Design. This was a case series of post-cardiac arrest patients undergoing ECPR.

Study Setting and Population. Patients in cardiac arrest or immediately post-cardiac arrest with poor systemic perfusion were considered candidates for therapy. Patient referrals were solicited from the ED and inpatient services of our institution. The enrollment process began with a primary service (ED or other) identifying a potential candidate. These services were frequently reminded of the availability of the therapy, and discussions of individual cases were made a part of emergency medicine, internal medicine, and surgery resident conferences. However, as the ECPR team did not attend every cardiac arrest in the institution, patient enrollment was reliant on referral from primary services. Once notified, the ECPR team, at the patient's bedside, made the final determination of eligibility. Barring pre-existing conditions believed to preclude meaningful long-term survival, any adult or child was considered a candidate for treatment. Relative contraindications included arrest time >30 minutes or profound metabolic acidosis (pH < 7.0). Patients who sustained cardiac arrest during initiation of ECMO for respiratory distress syndrome were not included in our review.

The ED (52,000 visits annually), inpatient units, operating rooms (ORs), and diagnostic suites of a tertiary care university hospital (820 beds) were the setting for initiation of the ECPR protocol.

Extracorporeal CPR was considered a heroic measure that had to be instituted within minutes of first patient contact. As such, and given that patient randomization was not part of our protocol for this study, our institutional review board did not require informed written consent prior to the initiation of therapy. However, immediately upon patient stabilization, an extensive informed consent document that encompassed ECPR as well as several related surgical procedures and research data collection was presented to the family.

Clinical Protocol

Establishing Extracorporeal Support. Initiation of venoarterial ECPR began with the cannulation of a major vein (the drainage cannula) and artery (the infusion cannula). The femoral vessels were most often used, although the right internal jugular vein and right common carotid artery were occasionally used. Access was achieved most often with a percutaneous, guidewire-based technique, and as necessary, with open identification and cannulation of the vessels. The carotid artery was always accessed in an open fashion. In adults, the preferred venous drainage line was a custom-built 23-Fr, thin-walled, wire-reinforced cannula (Medtronic Biomedicus, Eden Prairie, MN) with a similar 21-Fr line used for arterial reinfusion. Appropriately smaller cannulae were used in children using similar placement techniques. Cannulation typically required between 10 and 30 minutes. The procedure could be completed most quickly in patients with pre-existing central vascular catheters, such as individuals in the ICU or undergoing cardiac catheterization. Upon successful access to both vessels, patients received 100 U/kg of IV heparin to prevent clotting of the ECPR circuit.

Extracorporeal CPR provides cardiopulmonary support by drawing blood from a venous drain, pumping it through an oxygenator, and delivering it into the arterial circulation. Over the study period a variety of pumps and oxygenators were used as technology improved and our experience increased. The principal components in the system as currently configured are shown in Figure 1. A small, easily transported centrifugal pump (Delphin II, Sarns-3M, Ann Arbor, MI) was used to power the system. The performance of the centrifugal pump, much like the native heart, is reliant on the adequacy of venous drainage. When conditions were ideal, the device could generate in excess of 5 L/min of blood flow in adults. Although typically run from a standard wall electrical source, the pump could operate from an internal battery for as long as 90 minutes when necessary, allowing transport of the patient within the hospital. Attached to the venous return line of the centrifugal pump via a Y-connector was a reservoir for the rapid infusion of blood or other fluids into the patient. When this line was opened, packed red blood cells (RBCs) or other resuscitation fluids could be administered at rates in excess of 3 L/min. A 2.3-m^2 hollow-fiber oxygenator (Maxima Plus PRF, Medtronic Cardiovascular, Anaheim, CA) attached to a standard oxygen source was used to oxygenate blood being returned to the arterial circulation. Prior to the initiation of ECPR, the circuit was primed first with carbon dioxide (to prevent bubble formation), then with 2 L of crystalloid solution (Normosol, pH = 7.4, Abbott, N. Chicago, IL). Two grams of calcium chloride (to prevent hypocalcemia during the institution of ECPR) and 12.5 grams of human albumin (to passify the surface of the circuit) completed the priming solution.

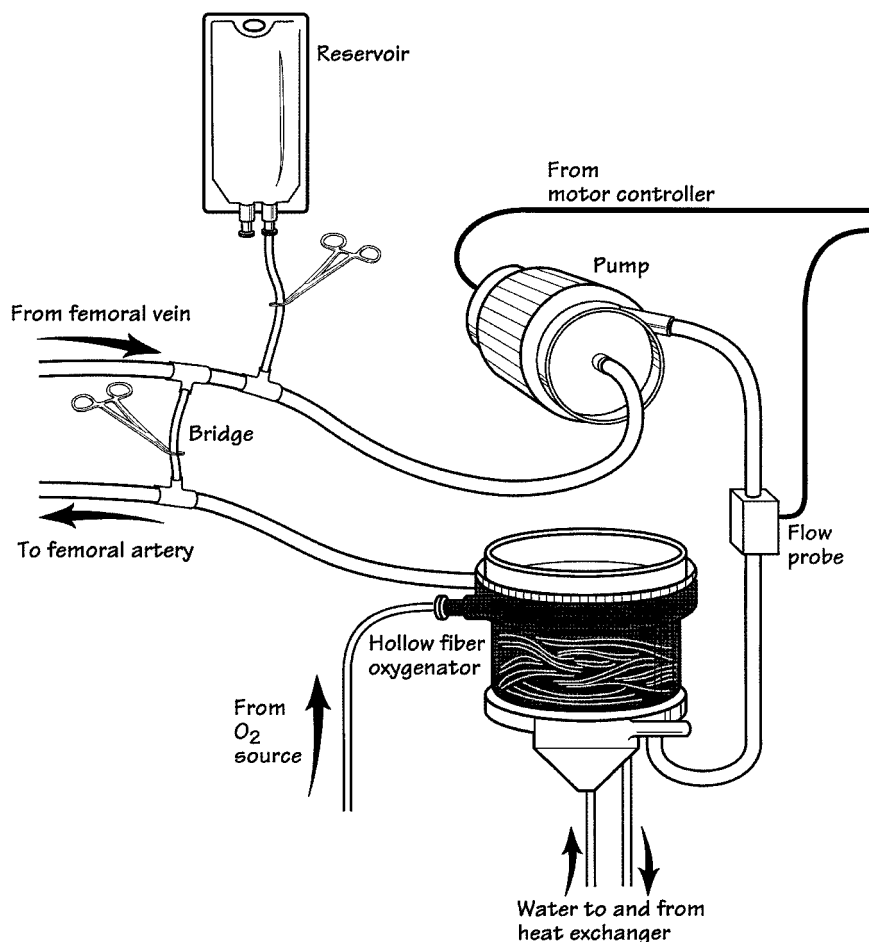While this circuit design was chosen because of

Figure 1. Extracorporeal cardiopulmonary resuscitation circuit currently used at our institution (see text for details and technical specifications).

the rapidity with which it could be primed (5 minutes), two major technical limitations existed. The first was the tendency of the microporous oxygenator to begin leaking plasma during the first 24 hours of use. The second was the propensity of the centrifugal pump to cause hemolysis (a result of the continuous suction placed on the venous drainage cannula). Accordingly, in patients surviving the first 24 hours, the ECPR circuit was discontinued and a long-term ECMO circuit was used for the remainder of therapy. This circuit included a roller pump (Cobe Roller Pump, Cobe, Inc., Arvada, CO) and solid membrane oxygenator (i4500, Avecor, Brooklyn Park, MN) to overcome the shortcomings of the ECPR equipment design.

In addition to these components, a variety of circuit and patient monitoring equipment was also needed to provide support. For the ECPR circuit, these included a venous oxygen saturation monitor to track the hemoglobin saturation of blood entering the pump, pre- and post-lung manometers to follow the performance of the hollow-fiber lung, and a thermostat-controlled heat exchanger to maintain patient temperature. Patient monitoring included continuous ECG, arterial blood pressure

(BP), arterial oxygen saturation, pulmonary arterial pressure, and pulmonary arterial oxygenation measurements. Systemic anticoagulation was maintained with continuous heparin infusion and monitored hourly with measurement of activated clotting times. These were routinely kept between 180 and 200 seconds.

Patient Management.   Once extracorporeal support was achieved, all patients were transferred to the surgical intensive care unit, unless an emergent diagnostic procedure was indicated (e.g., cardiac catheterization). To maximize oxygen-carrying capacity, packed RBCs were transfused to achieve a hematocrit of 40%. To minimize native cardiac work, ECPR pump flow was kept at the highest attainable rate. Patients were weaned from vasopressors to maintain a mean arterial pressure of 65 mm Hg, and sodium bicarbonate was administered to return the arterial pH to at least 7.30.

As soon as perfusion was stabilized, the cause of arrest was investigated with transthoracic or transesophageal echocardiography, cardiac catheterization, pulmonary angiography, or other diagnostic tests. Treatment of the underlying condition was instituted as soon as possible.

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Regardless of etiology, in some patients the stunned left ventricle was unable to generate sufficient pressure to open the aortic valve against the systemic arterial pressure generated by the ECPR circuit. In these instances, the left ventricle would continue to slowly fill with blood draining from the pulmonary and thebesian veins. Progressive overdistention of the ventricle during cardiopulmonary bypass can result in elevated transmural pressure and cardiac ischemia as well as pulmonary venous hypertension and alveolar flooding.[13] Therefore, patients whose arterial pressure tracings revealed no pulsatility (i.e., no contribution of the native heart) or in whom there was echocardiographic or angiographic evidence of a persistently closed aortic valve were taken for a left ventricular venting procedure. This was accomplished by percutaneous atrial balloon septostomy, which was performed with both fluoroscopic and transesophageal echocardiographic guidance by an interventional cardiologist. Successful septostomy was confirmed by echocardiographic visualization of an atrial defect and catheter manometry of both atrial chambers.

As the hollow-fiber oxygenator was responsible for the majority of gas exchange, the patient's arterial partial pressure of carbon dioxide (pCO_2) was primarily determined by the rate of gas flow through the device rather than the alveolar ventilation provided to the native lung. "Lung rest" was instituted using pressure-controlled mechanical ventilation in assist-control mode with a peak end-inspiratory pressure of 30 cm H_2O, positive end-expiratory pressure of 10 cm H_2O, a respiratory rate of 6 breaths/min and a fractional concentration of oxygen in inspired gas (FiO_2) of 50%. Following cardiac arrest, patients were typically volume-overloaded, and so diuresis was actively pursued with IV furosemide to achieve urine output of at least 100 mL/hr in adults. In instances where this goal could not be reached, renal replacement therapy in the form of continuous hemofiltration was used. The complex and dynamic course of ECPR patients required that in addition to routine critical care nursing care, specially trained ECMO specialists (either nurses or respiratory therapists) were physically present at the bedside continuously for the duration of therapy. ECMO fellows and a group of attending physicians, including an emergency physician and one pediatric and three general surgeons, provided additional care.

Given that treated patients were largely supported by artificial means, ROSC, as traditionally defined, was not a meaningful endpoint in this study. ROSC for our purpose was defined as successful resumption of native cardiac function following discontinuation of the ECPR circuit. Weaning of ECPR was instituted as soon as a patient's underlying illness had been addressed and there was evidence of return of native cardiac output. Weaning was attempted by increasing the FiO_2 and minute ventilation provided by the mechanical ventilator, then clamping off the extracorporeal circuit. A successful trial was in general one in which mean arterial BP was sustained above 65 mm Hg, mixed venous oxygen saturation was maintained above 60%, and pulmonary arterial systolic pressure did not rise above 50 mm Hg. When these goals could be maintained for several hours, the ECPR circuit was cut from the intravascular cannulae, which were then infused with heparin for no more than 24 additional hours. Catheters that had been placed with an open technique were removed with a small surgical operation to repair the instrumented vessels. Percutaneously placed catheters were simply removed, with continuous pressure applied to the insertion site for 30 minutes or until hemostasis was achieved. Subsequent critical care and inpatient management was provided by the general surgery service at our institution.

The decision to discontinue efforts and withdraw support, made in conjunction with family, was based on the duration and intensity of arrest, the patient's clinical appearance following institution of ECPR, and the potential reversibility of the patient's underlying condition.

Research Protocol and Outcome Measures. Data sources included a special ECPR flow sheet maintained hourly by the bedside ECMO specialist, and notes from the ICU nursing staff, respiratory therapists, and physicians. Our principal outcome was survival, which included discharge from the hospital or successful placement of a ventricular assist device as a bridge to cardiac transplantation.

Although the records of patient care once ECPR had been initiated were extensive, details of the arrest period were often incomplete. However, in all but one case we were able to reassemble the events occurring prior to and during the cardiac arrest. The duration of arrest was defined as the elapsed time from recognition of arrest to institution of extracorporeal support. Specific records of the ECPR team's response time or the time required to initiate bypass once the team arrived were in almost no case accurately recorded, and so a precise measurement of the time required to initiate ECPR was not possible (although as mentioned above, under optimal conditions cannulation typically required 10 to 30 minutes). The duration of extracorporeal support prior to death or successful weaning was defined as the elapsed time from initiation of ECPR flow to the final disconnection of the circuit from the intravascular cannulae.

TABLE 1. Characteristics and Outcomes of Patients Undergoing Extracorporeal Cardiopulmonary Resuscitation (ECPR)

Diagnosis	Age (years)	Location of Arrest	CPR Time (min)	ECPR Time (hours)	Flow (mL/kg/min)	Comments
Nonsurvivors						
Drowning	4	Out of hospital/ED	58	—	—	Unable to cannulate
Drowning	15	Out of hospital/ED	26	13	80	
Drowning	41	Out of hospital/ED	30	<1	66	
Cardiac tamponade following atrial septal defect repair	4	Inpatient ward	20	19	84	
Viral cardiomyopathy	23	CCU	Unknown	270	67	Atrial septostomy needed; experienced distal limb ischemia below infusion cannula
Viral cardiomyopathy	47	CCU	30	134	62	Atrial septostomy needed; converted to BiVAD; died following day
Aortic valve endocarditis	35	ED	15	155	46	Inoperable endocarditis; support withdrawn
AMI	30	CCU	67	20	43	Atrial septostomy required
AMI	39	Labor and delivery	55	—	—	Unable to cannulate
AMI	48	ED	35	258	44	Atrial septostomy needed; received LVAD as bridge to transplant; died of MSOF postoperatively
Cardiac arrest of uncertain etiology	48	SICU	5	<1	50	Pulmonary artery exploration revealed no pulmonary embolus
Pulmonary embolus	37	Angiography suite	50	—	—	Unable to cannulate; venous cannula inadvertently placed in femoral artery
Respiratory arrest	53	SICU	130	—	—	Unable to cannulate
Died after return of autonomous circulation						
Primary pulmonary hypertension	26	Cardiac catheterization lab	4	146	59	Recurrent right heart failure post-ECPR; second episode of ECPR undertaken with death due to MSOF
Ischemic cardiomyopathy	32	CCU	41	48	36	Patient died of recurrent ventricular arrhythmias
AMI	51	Cardiac catheterization lab	78	70	27	Below-knee amputation from arterial cannula complication; died of MSOF
Survivors						
Airway hemorrhage following liver transplant	55	SICU	8	21	30	Returned to independent living
Pulmonary embolus	22	Cardiac catheterization lab	55	35	55	Intracerebral hemorrhage necessitating surgical evacuation; mild expressive aphasia at one-year follow-up; returned to work
Pulmonary embolus	36	SICU	53	69	57	Returned to work
Pulmonary embolus following spinal cord injury	37	Inpatient ward	8	21	31	Returned to independent living
Air embolus	27	OR	20	30	80	Checked self out of inpatient rehabilitation center; lost to long-term follow-up
Airway obstruction	36	Inpatient ward	32	9	78	Discharged to inpatient rehabilitation facility
Ischemic cardiomyopathy	59	CCU	5	47	58	Atrial septostomy required; received LVAD; awaiting heart transplant
AMI	27	Cardiac catheterization lab	29	47	50	Received heart transplant
AMI during electrophysiologic mapping of left ventricle	61	Electrophysiology lab	30	70	50	Received LVAD; awaiting heart transplant

AMI = acute myocardial infarction; CCU = cardiac care unit; ED = emergency department; SICU = surgical intensive care unit; BiVAD = biventricular assist device; LVAD = left ventricular assist device; MSOF = multisystem organ failure.

Data Analysis. Analysis consisted mainly of descriptive statistics, which were compared with Student's t-tests. Statistical significance was set at the 0.05 level, and all statistical procedures were performed using SAS 6.12 on a Windows95 platform (SAS Institute, Cary, NC).

RESULTS

Twenty-five patients were treated during the seven-year study period. Details of patient diagnoses, demographics, ECPR course, outcome, and complications can be found in Table 1. A summary diagram of patient outcomes is shown in Figure 2. Of the patients treated, three could not be cannulated and subsequently died. A fourth died after inadvertent percutaneous placement of both the venous drainage and arterial infusion catheters into the femoral artery. Four patients (16%) received ventricular assist devices, two of whom survived. Of the remaining patients, nine (36%) achieved ROSC. Of these, two (8%) patients died of late complications related to their underlying illnesses. Given the patients who were converted to left ventricular assist devices (LVADs) and those who achieved ROSC, overall survival was 36%.

In general, this was a young patient population (including two pediatric drowning victims and one child with post-cardiotomy tamponade in the nonsurvivor group). There was a nonsignificant trend toward higher age in survivors (nonsurvivors 33 ± 15 years, survivors 40 ± 14 years, p = 0.28), a reflection of uniform mortality among the treated children. The diagnoses among survivors and nonsurvivors were similar, with the exception of three nonsurvivors who drowned. These three individuals were the only patients in whom the precipitating event occurred outside of the hospital. Two additional patients sustained cardiac arrest in the ED; among the other patients, nine were treated in ICUs, six in cardiac catheterization or angiography suites, three in general care inpatient wards, one in the OR, and one in the labor and delivery triage area. Nonsurvivors received more prolonged conventional CPR prior to ECPR (nonsurvivors 43 ± 32 minutes, survivors 21 ± 16 minutes, p = 0.04).

Blood flow sufficient to support life was achieved in all patients successfully cannulated. Flow was not related to survival (nonsurvivors 55 ± 17 mL/min/kg, survivors 56 ± 15 mL/min/kg, p = 0.82). While no statistically significant difference between the durations of ECPR was found between survivors and nonsurvivors, survivors on average required support for half as long as nonsurvivors (nonsurvivors = 87 ± 96 hr, survivors = 44 ± 21 hr, p = 0.18). Except in the cases where resuscitative efforts were ceased during difficult cannula-
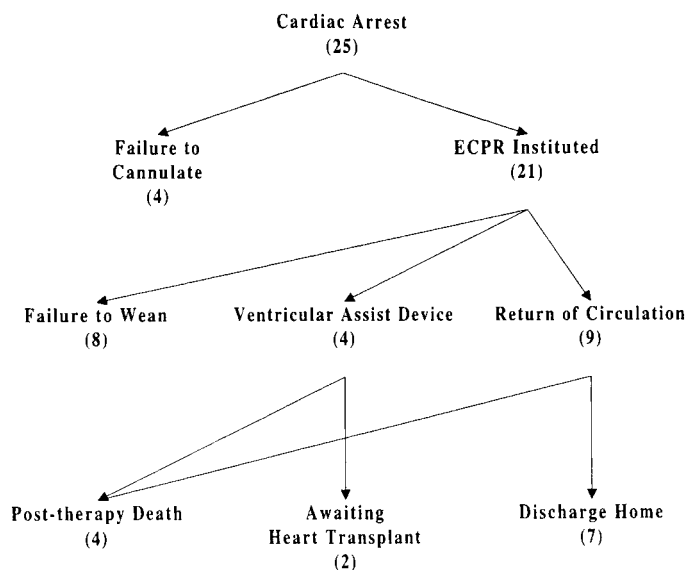

Figure 2. Outcome of patients treated with extracorporeal cardiopulmonary resuscitation (ECPR).

tion, no patient had support stopped for technical complications or equipment failure.

Cannulation was frequently accompanied by minor problems with hemostasis; major cannulation-related problems were uncommon. In two patients, flow to the leg below the arterial reinfusion cannula was jeopardized, requiring the insertion of small secondary cannulae to perfuse the involved extremity. In one of these patients (a nonsurvivor with advanced peripheral vascular atherosclerotic disease), leg ischemia persisted, ultimately necessitating a below-the-knee amputation. Other surgical complications included thoracotomy for diagnostic purposes or for the removal of intrathoracic or mediastinal blood in three patients and craniotomy for intracerebral hemorrhage in one. Continuous hemofiltration or hemodialysis was required in eight patients (32%) to support impaired native renal function. Atrial septostomy for left ventricular venting was indicated in one surviving and four nonsurviving patients (20%).

Of the nine patients with ROSC, seven (28%) were discharged from the hospital. The first patient to receive ECPR in our study, a 27-year-old man with end-stage cardiomyopathy, was on support for 47 hours before a donor heart was procured. The patient had ECPR discontinued in the OR at the time formal cardiopulmonary bypass was instituted. His transplant was successful and he subsequently was discharged from the hospital. The remaining six patients all had initial events of pulmonary origin (three with pulmonary thromboemboli, one with air embolism, and two with airway obstruction). Of these, four were neurologically normal at discharge and two had persistent mild neurologic deficits that did not prevent them from returning to work.

Two patients who achieved ROSC died during their hospitalizations. The first was a young woman with end-stage primary pulmonary hypertension who developed suprasystemic pulmonary arterial pressures during a right-heart catheterization and sustained a cardiac arrest. The patient was weaned from bypass after a 146-hour ECPR course, only to deteriorate and require a second course of extracorporeal support. She ultimately succumbed to progressive multisystem organ failure when no suitable heart–lung donor was located. A second patient developed refractory ventricular tachycardia following multivessel coronary artery bypass graft surgery for severe ischemic cardiomyopathy. He was weaned from ECPR after 41 hours and successfully extubated the following morning. While arrangements for heart transplant were being made, the patient sustained another dysrhythmic cardiac arrest and died.

Four patients who did not achieve ROSC were converted from ECPR circuits to ventricular assist devices; one received a biventricular assist device (BVS 5000 temporary artificial heart system, Abiomed, Danvers, MA) and three received long-term implantable LVADs (HeartMate, Thermo Cardio Systems, Waltham, MA). Two of these patients had recognized severe coronary artery disease prior to their cardiac arrests, one was found to have severe inoperable multivessel coronary artery disease after experiencing sudden cardiac death in the ED, and one sustained cardiac arrest secondary to viral myocarditis. The patient with myocarditis died the day after placement of the biventricular assist device. The patient placed on ECPR in the ED developed pancreatitis and multisystem organ failure following placement of the LVAD and later died. The other two LVAD recipients recovered fully, are undergoing physical rehabilitation, and await cardiac transplantation.

DISCUSSION

We found that extracorporeal circulation can aid in the resuscitation of patients with cardiopulmonary arrest. Our 36% rate of survival is higher than would be expected from the published reports using traditional CPR. It is also consistent with prior reports of extracorporeal resuscitative techniques.[3,9,14–16] Our experience with the care of patients in the ED was limited, but is consistent with that reported in the largest ongoing series of patients treated with ECPR, the National Cardiopulmonary Support Registry for Emergent Applications. This patient registry has noted a decreased likelihood of long-term survival for patients treated with ECPR in the ED. Of patients treated in the EDs of participating centers, 14 of 19 (73.7%) never achieved ROSC.[17]

In their report of one of the earliest ECPR patient series, Mattox and Beall in 1976 predicted that given the recent progress in simplifying and miniaturizing equipment, cardiopulmonary bypass might become a practical means of CPR in many hospitals.[9] While experience with the technique has grown over the subsequent two decades, the availability of the method remains very limited, and we know of no ED in the United States performing ECPR regularly. We believe there are several important challenges to be mastered before ECPR can become more widely available.

As with all clinical CPR research, optimum patient selection remains a daunting problem. Most patients sustaining cardiac arrest at the end of a prolonged illness, at a very advanced age, or a prohibitive distance from a hospital likely would not benefit from ECPR. Rather, the patients most likely to respond are those in whom vital signs are initially present but in whom arrest occurs during evaluation or treatment. Such individuals might suffer from curable illnesses such as pulmonary embolism or surgically amenable coronary artery disease. In our series and others, such entities were often successfully treated with ECPR.[18] However, unlike in previous reports, no patient in our study had coronary artery disease amenable to either percutaneous transluminal coronary angioplasty or bypass grafting alone.

Successful ECPR requires being able to rapidly bring together the patient, the ECPR device, and personnel able to both initiate therapy and deal with potentially lethal complications. At our institution the ECPR device is pre-assembled and can be primed while the patient is undergoing cannulation. While physicians are immediately available typically only during the day, an ECMO specialist is in the hospital at all times. This facilitates rapid preparation for ECPR at night.

The most frequent complications we encountered were related to bleeding. Interventions required included thoracotomy, craniotomy, and amputation. In patients anticoagulated for the purpose of extracorporeal blood flow, surgical procedures can be technically challenging. Accordingly, the immediate availability of surgical collaborators is probably prerequisite to any ECPR program. Diagnostic assistance with echocardiography, cardiac catheterization (with atrial balloon septostomy capability), and pulmonary angiography is also needed.

The traditional paradigm of recovery from cardiac arrest is one of "all or nothing." Patients who develop cardiopulmonary function capable of at least the short-term support of life are sent to the ICU, and the rest are pronounced dead. Most patients are thus dichotomized in less than an hour of the onset of arrest. Animal models of cardiac ar-

rest using extracorporeal support have largely reproduced this practice. Safar and colleagues have amassed an extensive experience with partial cardiopulmonary support in a variety of canine models of ventricular fibrillation.[8] However, their longest duration of bypass was four hours. Human experience suggests that resuscitation with ECPR in humans may need to be much more prolonged. Willms and coworkers noted during their ten-year experience with ECPR that the average duration of extracorporeal support grew from 185 minutes in their first patients to more than 34 hours in their most recent 24 patients.[15] In reporting their study of emergency cardiopulmonary bypass in the ED (using a protocol that withdrew support following six hours of therapy), Martin and colleagues comment that longer cardiac support might have been beneficial in patients showing signs of early neurologic recovery in the face of persistent cardiac failure.[19] The requirement for prolonged mechanical cardiac support underscores that ECPR is not as much an extension of current advanced life support techniques as a different paradigm of the treatment of cardiac arrest altogether. The strategy of rapid reperfusion followed by prompt discontinuation of extracorporeal support while still in the ED or within hours of arrest seems unlikely to be successful.

LIMITATIONS AND FUTURE QUESTIONS

The chief limitation of our study and of all the human ECPR data published thus far is the means by which patients were selected for treatment. Approximately 2,000 cardiac arrests occurred at our institution during patient accrual for this report; we treated less than 1% of them. While clinical experience suggests that the chance of any patient in cardiac arrest ever leaving the hospital is quite small, we cannot definitively state that we impacted the outcome of the patients selected in our study. Furthermore, the extent to which our results might be generalized to a more widespread application of ECPR remains to be seen.

CONCLUSION

Extracorporeal CPR, when applied to selected cases of cardiac arrest, led to 36% survival rate in our study. In both survivors and nonsurvivors, the duration of therapy typically extended beyond 24 hours and was associated with a variety of minor and major, primarily surgical complications. Broader experimental application of this technology is needed to more fully identify patients whom it may serve and methods by which it can be most quickly and safely administered.

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