A healthy 14-year-old presented to an emergency department in Alaska, complaining of shortness of breath, chest pain, and 72 hours of malaise and headache. On admission, her blood pressure was 80/50 mm Hg, and she had cool extremities. Electrocardiography revealed wide-complex ventricular tachycardia. She underwent synchronized electrical cardioversion. Although she initially converted to sinus rhythm, she subsequently became pulseless, with electrocardiographic evidence of ventricular tachycardia. Despite cardiopulmonary resuscitation, she failed to achieve a perfusing rhythm. Cardiovascular surgery consultation was obtained, and she was placed on partial cardiopulmonary bypass during 2 hours of ongoing chest compressions. Cardiopulmonary bypass flow was limited by the small size of her femoral arteries. She remained in refractory ventricular tachycardia. The cardiopulmonary bypass circuit was modified for transportation of the patient via air ambulance 1500 miles to a tertiary medical center that specializes in pediatric heart failure and mechanical cardiopulmonary support. Upon arrival at the tertiary medical center, she underwent carotid artery cannulation to improve total cardiopulmonary support and percutaneous balloon atrial septostomy to facilitate left ventricular decompression. Intravenous immunoglobulin and steroids were administered to treat presumed acute fulminant viral myocarditis. Extracorporeal life support was support was successfully discontinued after 14 days, but she experienced a thromboembolic stroke. The patient was discharged on hospital day 65 with moderate generalized left-sided weakness, but she was able to ambulate with minimal assistance. She subsequently returned to school and is progressing appropriately with her peers. Cardiac function has normalized, and she remains in normal sinus rhythm. Pediatrics 2013;131:e1–e5
Approximately 1% to 2% of all pediatric patients who are admitted to a hospital will require cardiopulmonary resuscitation (CPR) for acute cardiopulmonary failure.\textsuperscript{1,2} Despite the publication of standardized Pediatric Advanced Life Support consensus recommendations\textsuperscript{3} and subsequent evidence-based revisions,\textsuperscript{4} overall survival from in-hospital cardiac arrest and CPR has remained <30% for >50 years.\textsuperscript{5-7} Effective CPR and early return of spontaneous perfusing cardiac rhythm are associated with improved survival, whereas survival in patients after >60 minutes of CPR is rare.\textsuperscript{8,9}

The application of extracorporeal life support during cardiopulmonary resuscitation (ECPR) has been shown to improve survival in adults\textsuperscript{10} and children.\textsuperscript{11} Recognition of this improved survival benefit has led to increased use of ECPR over time, with >2400 cumulative cases reported to the Extracorporeal Life Support Registry in 2011.\textsuperscript{12} However, the provision of salvage extracorporeal life support is costly\textsuperscript{13} and generally requires dedicated hospital resources, which restricts universal availability of this therapeutic option. Despite these limitations, ECPR may be used on an ad hoc basis in centers without a dedicated extracorporeal life support program. This report describes the case of a child who received ECPR in a hospital that does not provide extracorporeal membrane oxygenation (ECMO) services and the subsequent transportation of the child to a center that specializes in extracorporeal life support.

**PATIENT PRESENTATION**

In October 2010, a previously healthy 14-year-old girl (57 kg, 163 cm in height) presented to the emergency department of a hospital in Alaska, complaining of shortness of breath and chest pain. She described malaise, dizziness, anorexia, and headache during the preceding 72 hours and denied recreational drug use. On admission, her blood pressure was 80/50 mm Hg, and she had cool extremities. Electrocardiography revealed wide-complex ventricular tachycardia with a heart rate of 130 beats per minute. She underwent sedated, biphasic synchronized electrical cardioversion with 150 J. Although she initially converted to sinus rhythm for 90 seconds, she subsequently became pulseless, with electrocardiographic evidence of ventricular tachycardia. CPR was initiated. Nonperfusing, wide-complex ventricular tachycardia was refractory to additional multiple additional attempts at electrical cardioversion (200 J) and administration of sodium bicarbonate, calcium chloride, lidocaine, amiodarone, and milrinone. During resuscitation efforts, femoral venous and arterial catheters were inserted. The adequacy of CPR was ascertained by the presence of palpable femoral pulses and pulsatile arterial catheter tracings during chest compressions. CPR was briefly (<1 minute) discontinued intermittently to perform transthoracic echocardiographic imaging. The patient had no spontaneous circulation during these periods. Echocardiography revealed left ventricular dilation with severely depressed systolic function. The patient developed significant acidemia (arterial blood pH = 7.1).

Cardiovascular surgery consultation was obtained for urgent mechanical cardiopulmonary support. The patient was taken to the operating room where she was noted to have hemorrhagic pulmonary edema. Partial cardiopulmonary bypass was initiated using right femoral artery (14F catheter) and vein (22F catheter) cannulation during ongoing chest compressions. Cardiopulmonary bypass flow was limited (20 mL/kg per minute) by the small size of the femoral artery, which prevented insertion of a larger cannula. The total duration of CPR had been 2 hours when cardiopulmonary bypass was initiated. Although arterial pH improved from 7.07 to 7.31 during 1 hour of femoral-femoral bypass, the patient remained in refractory ventricular tachycardia and required epinephrine infusion to maintain systolic blood pressure near 100 mm Hg. The cardiopulmonary bypass circuit, which consisted of a Medtronic BP80 centrifugal pump, an Affinity NT oxygenator, and a Bio-Console 560 Speed Controller System (Medtronic, Minneapolis, MN), was configured to enable cardiopulmonary bypass support of the patient during transportation via air ambulance 1500 miles to Seattle Children’s Hospital, a center that specializes in pediatric heart failure and mechanical cardiopulmonary support. Continuous epinephrine infusion with additional intermittent boluses, packed red blood cells, and sodium bicarbonate were administered during transportation to maintain adequate blood pressure.

Upon the patient’s arrival at Seattle Children’s Hospital, she had wide-complex tachycardia (140 beats per minute), hypotension, anuria, and bloody pulmonary edema. Left ventricular systolic dysfunction and dilation were noted by transthoracic echocardiography. Additional attempts at electrical cardioversion were unsuccessful. The patient was taken to the operating room and underwent exchange of the 14F femoral artery catheter for a 19F right common carotid catheter and insertion of an additional 23F right internal jugular catheter to improve total cardiopulmonary support. She was then transferred to the cardiac catheterization suite, where she underwent percutaneous balloon atrial septostomy and placement of a stent across the foramen ovale to facilitate left ventricular decompression. Although an endomyocardial biopsy may have proven
beneficial in this patient’s clinical management, a biopsy was not performed at that time. Continuous intravenous amiodarone infusion was initiated. The patient was cooled to 34°C and subjected to pharmacologic muscle relaxation for 72 hours to reduce oxygen demand. Renal function briefly improved after achieving improved ECMO support, consistent with the presence of acute tubular necrosis related to prolonged resuscitation and limited ECMO perfusion. However, she subsequently experienced increasing serum creatinine levels and complete anuria, necessitating the addition of continuous renal replacement therapy to the ECMO circuit. Continuous renal replacement therapy was discontinued with a return of intrinsic renal function after 10 days of ECMO support.

The patient’s history, presentation, and echocardiographic findings were consistent with the diagnosis of acute fulminating myocarditis. Serum viral titers, which were obtained because of the presumed diagnosis of viral myocarditis, were negative. Intravenous immunoglobulin and steroids were administered. Although the patient converted to sinus rhythm within 48 hours of ECMO, she required intravenous lidocaine infusion and electrical cardioversion for intermittent return of ventricular tachycardia. Serial transthoracic echocardiographic evaluations revealed improved ventricular function. She began to follow commands on the 11th day of mechanical cardiopulmonary support. ECMO was discontinued after 14 days and cannulae were removed. Reconstruction of the right common carotid artery and internal jugular vein was performed. The following day, the patient was noted to exhibit left-sided weakness. The results of computed tomographic cerebral angiography were consistent with focal embolic occlusion of the right middle cerebral artery, without evidence of hemorrhagic sequelae. Subsequent MRI confirmed an acute focal infarct but did not indicate diffuse hypoxic ischemic brain injury. Mechanical ventilation was discontinued, and the patient was extubated 4 days after discontinuation of ECMO. She was transitioned to oral amiodarone, carvedilol, warfarin, and tapered prednisone.

The patient was discharged on hospital day 65. At the time of discharge she exhibited moderate generalized left-sided weakness but was able to ambulate with minimal assistance. She has returned to school where she participates in competitive sports and continues to be an “A” student. She has no discernable physical or intellectual sequelae of cerebral infarct. Cardiac function has normalized, and she remains in normal sinus rhythm.

DISCUSSION

This case highlights the importance of appropriately performed CPR and the improved survival associated with the use of ECPR. Although overall survival in patients requiring CPR for acute cardiopulmonary failure has remained <30% for more than half a century, survival of individual patients appears to correlate with early initiation of CPR and the quality of CPR being performed. Myocardial, cerebral, and peripheral oxygen delivery during CPR is dependent on external compressive forces that squeeze the heart between the sternum and spine to forcibly eject blood into the pulmonary and systemic circulations. The appropriate timing and force of compressions are critical to achieve optimal systemic perfusion and oxygen delivery. It has been shown that systemic blood pressure and end-tidal carbon dioxide, an indicator of pulmonary perfusion, directly correlate with the compressive force applied during CPR, with compressive forces >16.7 pounds per square inch producing the greatest changes in these indexes in adults. However, the quality of CPR chest compressions decreases quickly, with only 18% of chest compressions being performed correctly after 3 minutes of CPR by a single provider. This may be an important contributing factor in the observation that 30-day survival decreases by 5% with each elapsed minute of CPR. The recently updated 2010 American Heart Association Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care recommend that the task of chest compressions should rotate every 2 minutes when multiple rescuers are available.

When compared with CPR alone, the use of ECMO as an adjunct to CPR has been shown to significantly improve survival in children and adults. By using a propensity-score–based analysis, Chen et al observed that adult patients who received ECPR were twice as likely to survive than patients who received conventional CPR alone when ECMO was initiated ≥30 minutes of arrest. Furthermore, the observed survival benefit of ECPR increased with longer duration of chest compressions. Although survival after 60 minutes of CPR is generally <1%, ~18% of the patients in their study who were placed on ECMO after 60 minutes of CPR survived to hospital discharge in their study. In contrast, a recent retrospective, single-center study in pediatric patients reported no survivors when ECPR was initiated after ≥50 minutes of CPR. It is unlikely that a randomized controlled trial of ECPR versus conventional CPR will ever be performed. However, the available data supporting a true survival benefit of ECPR are compelling enough that the American Heart Association Pediatric Advanced Life Support guidelines state that ECPR may be considered for children with a potentially reversible cause of cardiac arrest that is refractory to...
standard resuscitation attempts, because long-term survival is possible even after >50 minutes of standard CPR. As of October 2012, 88 centers in the United States have reported the use of ECPR to the Extracorporeal Life Support Organization, with overall survival rates ranging from 27% in adults to 39% to 41% in pediatric patients. ECMO and ECPR are costly therapeutic interventions. However, the results of several cost-effectiveness analyses suggest that increased ECMO-related hospital costs are justified on a cost-utility basis. The estimated cost-utility for salvage ECMO ranges from $20,880 to $24,386 per quality-adjusted life-year saved, which is less than half the cost of pediatric heart transplantation ($49,679 per quality-adjusted life-year saved). The cost-utility for ECPR and the effects of center volume and/or center centralization on cost-utility are unknown. Although no studies have critically examined the actual institutional costs of maintaining a dedicated ECMO program, ECMO equipment and personnel costs are not insignificant. Many low-volume centers may find the cost of developing and maintaining ECMO and ECPR programs to be prohibitively expensive. However, maintaining an in-house rapid-response ECPR team and preprimed ECMO equipment is not necessary to perform ECPR. Most centers that perform cardiac surgery possess the basic equipment that is necessary to perform ECPR on an ad hoc basis. As described in this report, a standard cardiopulmonary bypass circuit may be modified for use as an ECPR circuit and then used to support a patient during transportation to a center that specializes in heart failure and extracorporeal life support. The risks and challenges of applying ECMO, a highly complex therapy, in an unusual setting must be weighed against the potential survival benefit of ECPR. Standard inclusion and exclusion criteria for ECPR have not been established. Although it seems intuitive that ECPR survival should be greatest in otherwise healthy patients with few comorbid conditions who experience a witnessed cardiac arrest with immediate and adequate CPR, the decision to initiate ECPR is ultimately based on the availability of resources and clinical judgment of care providers. Studies that provide information related to optimal patient selection, survival, and complications of ECPR in low-volume centers would be welcome additions to the literature.

The transportation of ECMO patients by ground and air ambulance has been performed by a number of centers in the North America, Europe, Asia, and Australia. In most cases, a specialized ECMO center sends a team to the requesting hospital to place the patient on ECMO and then the patient is transported to the specialized center. Although the safety and effectiveness of this approach have been demonstrated, the interval of time between initial request and initiation of ECMO support is typically several hours. Consequently, such a process is not applicable in situations in which a patient has experienced cardiac arrest and is receiving chest compressions. However, establishing some form of extracorporeal life support after cardiac arrest can stabilize patients so that arrangements can be made for transportation to a center that specializes in extracorporeal life support, as this case clearly illustrates.

In summary, survival after cardiac arrest is dependent on several factors, not the least of which are the resuscitation team's determination and willingness to explore every therapeutic strategy. The heroic efforts of this child's initial care providers enabled her to be rescued by using ECPR, even without a dedicated ECMO/ECPR program, and transported to a specialized center. This case highlights the notion that the survival benefits of ECPR may be applicable to patients across a broader spectrum of medical centers.

"Never give up, for that is just the place and time that the tide will turn."
—Harriet Beecher Stowe

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