International Journal of Cardiology 176 (2014) 828–832

Contents lists available at ScienceDirect

International Journal of Cardiology

journal homepage: www.elsevier.com/locate/ijcard

Novel techniques of mechanical circulatory support for the right heart and Fontan circulation ☆

Gwendolyn Derk [a,b,*], Hillel Laks [b], Reshma Biniwale [b], Sanjeet Patel [b], Kim De LaCruz [e], Einat Mazor [d], Ryan Williams [a], John Valdovinos [c], Daniel S. Levi [f], Leigh Reardon [a,f], Jamil Aboulhosn [a,f]

[a] Ahmanson/UCLA Adult Congenital Heart Disease Center, UCLA Division of Cardiology, United States
[b] UCLA Cardiothoracic Surgery Department, United States
[c] UCLA Bioengineering Department, United States
[d] UCLA Anesthesiology Department, United States
[e] UCLA Cardiac Perfusion Services, United States
[f] UCLA Division of Pediatric Cardiology, United States

ARTICLE INFO

Article history:
Received 29 June 2014
Accepted 2 August 2014
Available online 8 August 2014

Keywords:
Ventricular assist device
Congenital
Heart failure

ABSTRACT

Background: Currently available ventricular assist devices are designed primarily for use in patients with left sided heart failure. This study evaluated the efficacy of the Jarvik 2000 ventricular assist device (VAD) as a pulmonary pump to power a Fontan circuit in a large animal model.
Methods: Without the use of cardiopulmonary bypass, Fontan circulations were surgically created in 4 pigs (50 kg) using synthetic grafts from the inferior and superior vena cavas to the main pulmonary artery. Subsequently, the VAD was implanted within the common Fontan graft to provide a pulmonary pump. Direct chamber pressures and epicardial Doppler images were taken during the various phases of the experiment. Heart rate, femoral artery blood pressure, oxygen saturation, and aortic flow rate were continuously recorded. The outflow cannula of the VAD was then partially banded by 50% and then 75% to mimic increased afterload.
Results: Fontan and VAD implantation was successfully performed in all 4 animals. Arterial pressure and aortic flow decreased dramatically with institution of the Fontan but were restored to baseline upon activation of the VAD. The pressure within the systemic venous circulation rose precipitously with institution of the Fontan circulation and improved appropriately with activation of the VAD. Adequate perfusion was maintained during increased afterload.
Conclusions: An axial flow VAD can restore normal hemodynamics and cardiac output when used as a pulmonary pump in a Fontan circulation. A VAD can rescue a failing Fontan as a bridge to transplant or recovery, even in the setting of high pulmonary resistance.

1. Introduction

Current ventricular assist devices are not designed for use in patients with complex congenital anatomy. Instead, their focus has been on patients with left sided heart failure. Patients with single ventricle physiology present a unique and challenging subset of patients at risk for developing heart failure [1]. Specifically, those that have undergone Fontan surgical palliation, whereby the systemic venous return is directly routed to the pulmonary arterial circuit without the use of an intervening pump, are at risk for chronic "right sided" heart failure [2]. The long-term outcomes of the Fontan operation include low cardiac output and elevated systemic venous pressure, resulting in a myriad of potential long-term complications including arrhythmias, hepatic abnormalities, renal dysfunction, mesenteric edema, and peripheral venous congestion, among others [1–4]. "Failing" Fontan patients may suffer from multiple organ dysfunction and are considered high risk candidates for orthotropic heart transplantation [5,6]. Numerous medical and interventional therapies may improve cardiac output and decrease central venous pressure, however, the benefits are often temporary. At the heart of the problem is the absence of a "right sided" pump to the pulmonary circulation.

We hypothesize that axial flow ventricular assist devices designed to aid the left heart could be used to create a pump to the pulmonary circulation which could result in normalization of cardiac output and systemic venous pressure. Several large animal models have been previously described and were created using a surgical approach with and without cardiopulmonary bypass [7–14]. We designed a large animal

☆ This study is funded by an investigator initiated grant from the Hertz Foundation (441357JC55902) to Dr. Aboulhosn, Ahmanson/UCLA ACHD Center, for research into treatment of congenital heart failure.

* Corresponding author at: 650 Charles E Young Drive South, Los Angeles, CA 90095, United States. Tel.: +1 805 797 9496 (cell), +1 310 825 2019 (business); fax: +1 310 825 6346.
E-mail addresses: grderk@gmail.com, gderk@mednet.ucla.edu (G. Derk).

http://dx.doi.org/10.1016/j.ijcard.2014.08.012
0167-5273/

experiment to surgically create a Fontan circulation and then evaluated the efficacy of the Jarvik 2000 ventricular assist device (VAD) as a "right sided" pump to power the Fontan circuit (Fig. 1A).

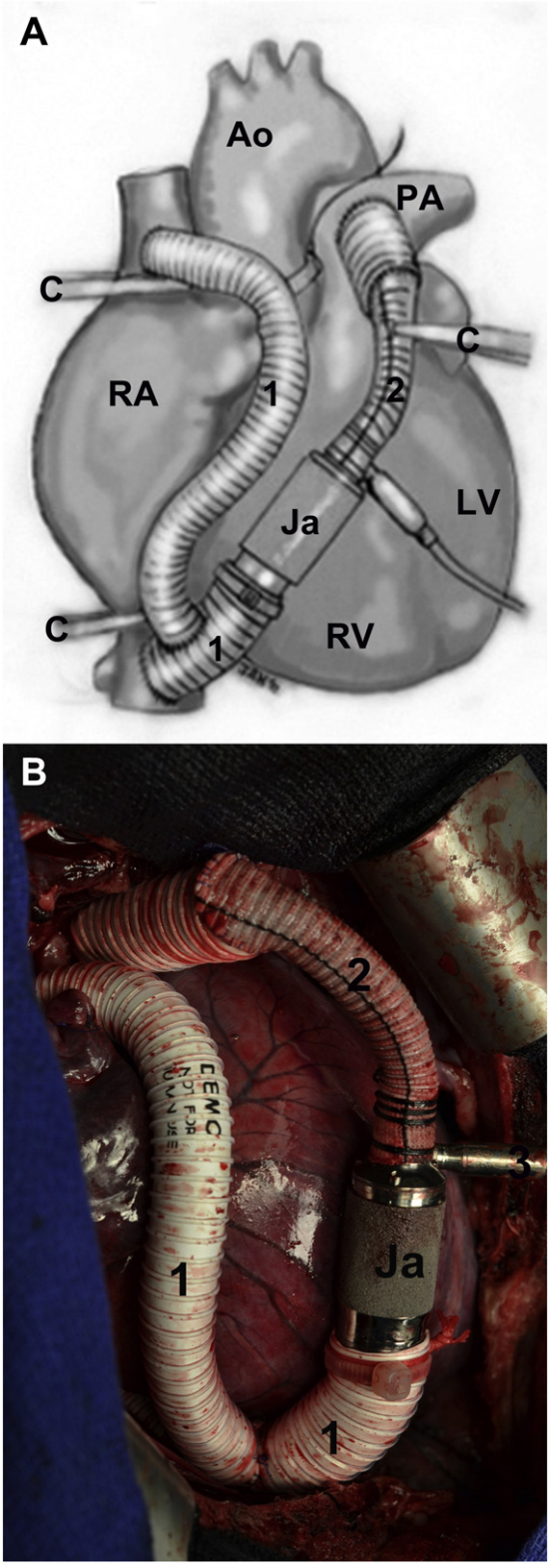

Fig. 1. Extracardiac Fontan model with the Jarvik 2000 VAD implanted. RA: right atrium; Ao: aorta; RV: right ventricle; LV: left ventricle; PA: pulmonary artery; Ja: Jarvik pump; 1: treated inflow Gore-tex graft; 2: Vascutek outflow graft (partially clamped to simulate increased afterload); 3: Jarvik power cord; C: clamp.

2. Methods

The experimental protocol was approved by the Animal Research Oversight Committee of the University of California in Los Angeles. All animals received humane care as mandated by the Animal Welfare Act and the Public Health Service Policy on Humane Care and Use of Laboratory Animals.

2.1. Animal preparation

Four Yorkshire Pigs (mean weight 50.7 kg, range 44.0 kg to 61.0 kg) were given pre-operative sedation via an intramuscular injection of Telazol and Atropine. The pigs were intubated and placed under general anesthesia on a mechanical ventilator. Seven French sheaths were placed in the right femoral artery and vein using the modified Seldinger technique and pressures were continuously monitored. A jugular venous sheath was also placed for drug administration and systemic venous pressure readings. A Foley catheter was placed and urine output was measured continuously throughout the procedure. Intravenous Cefazolin was given for prophylaxis before the surgery.

A midline sternotomy was performed. The pericardium was opened and the heart was suspended in the pericardium. The superior vena cava (SVC), the inferior vena cava (IVC) and the pulmonary arteries (PAs) were dissected free from surrounding structures. Heparin was administered as needed to keep the activated clotting time (ACT) in an acceptable range. Blood was suctioned into a cell saver device. Packed red blood cells were obtained from the cell saver device and administered if the hemoglobin count dropped below 8 g/dL. Additionally, occasional saline fluid boluses were given to counteract decreased blood pressure.

2.2. Data collection

Pressure from the femoral arterial and venous sheaths was recorded continuously throughout the experiment. Additionally, using a 20 gauge needle, direct pressure measurements were made in the IVC, SVC, left atrium and main PA at each phase of the experiment. Aortic flow was continuously monitored via a transonic flow probe fitted to the ascending aorta. The Transonic Perivascular Flow Meter continuously transmitted aortic flow measurements which were captured using National Instruments LabVIEW Software. Vitals including heart rate, femoral artery blood pressure, and systemic oxygen saturation were continuously monitored. Epicardial 2-D echocardiography with Doppler was performed at each phase of the experiment (GE Vivid 7). Left ventricular ejection fraction was visually estimated and left ventricular outflow tract pulse wave Doppler signals were measured to estimate stroke volume by velocity time integral (LVOT VTI). Vetscan i-STAT machine was used with CG8+ cartridges to obtain blood gases, activated clotting time (ACT), electrolyte, blood chemistry and hematology readings. These readings were performed every 30 min and at each phase of the experiment.

2.3. Creation of extracardiac Fontan

The Fontan circulation was created without the use of cardiopulmonary bypass. A C-clamp was placed vertically across the SVC just above the right atrial juncture without occluding SVC flow. The side of the SVC was incised and a 12 mm Gore-tex graft was sewn to the SVC in an end-to-side fashion. Silastic surgical glue was applied circumferentially to all suture sites. The graft was then clamped and the C-clamp on the SVC was released. The IVC was subsequently clamped and incised in a similar fashion just below the entry point to the right atrium. A 16 mm Gore-tex graft was sewn in an end-to-side fashion to the IVC. The 12 mm graft from the SVC was sewn in an end to side fashion to the 16 mm graft from the IVC. The 16 mm graft was then sewn to the main pulmonary artery in an end-to-side fashion. Another set of data points was taken prior to completion and opening of the Fontan circulation. To simulate the absence of a right heart pump and the completed Fontan circulation, the SVC and IVC were fully clamped at their entry site to the right atrium, therefore, systemic venous return was diverted from the right atrium and right ventricle via the Gore-tex conduits directly to the pulmonary artery. Pressure and flow measurements were gathered as described above.

2.4. Placement of axial flow ventricular assist device

The SVC and IVC were temporarily unclamped and the SVC and IVC grafts were clamped in order to allow systemic venous return to the right heart while the VAD was surgically implanted. The 16 mm graft was transected proximal to the entry point into the pulmonary artery and the VAD was inserted into the graft. The proximal inflow end of the 16 mm Gore-tex graft was secured over the VAD. The outflow graft of the VAD was a 10 mm Vascutek graft that was connected in an end-to-end fashion to the remaining 16 mm graft connected to the main pulmonary artery. The SVC and IVC were then clamped and the VAD was activated and flow rates were gradually increased over 15 min to a goal of 5 l/min. Flow and pressure measurements were taken at each of the 5 speed settings of the Jarvik 2000 (Table 1) (Fig. 1B).

2.5. Increased afterload simulation

To simulate increased pulmonary arterial pressure the outflow graft of the VAD was clamped by 50%. Subsequently, the outflow graft was clamped by 75% to simulate severely elevated afterload and measurements were again collected.