Effect of mechanical assistance of the systemic ventricle in single ventricle circulation with cavopulmonary connection

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Background: Previous attempts to support single ventricle circulation mechanically have suggested that a custom-built assist device is needed to push, rather than pull, through the pulmonary circulation. We hypothesized that using a conventional ventricular assist device, with or without conversion of a total cavopulmonary connection to a bidirectional Glenn cavopulmonary connection, would allow assistance by pulling blood through the circuit and improve the cardiac index (CI).

Methods: Cavopulmonary connections were established in each of 5 Yorkshire pigs (25 kg) using ePTFE conduits in a Y configuration with appropriate clamping of the limbs of the Y to achieve a total cavopulmonary Fontan connection (TCPC), superior vena cava cavopulmonary connection (SVC Glenn), and inferior vena cava cavopulmonary connection (IVC Glenn). A common atrium had been established previously by balloon septostomy. Mechanical circulatory assistance of the single systemic ventricle was achieved using a centrifugal pump with common atrial inflow and proximal ascending aortic outflow. The CI was calculated using an ultrasonic flow meter placed on the distal ascending aorta and compared between the assisted and nonassisted circulation for 3 conditions: TCPC, SVC Glenn, and IVC Glenn. The mean pulmonary artery pressure, common atrial pressure, arterial oxygen saturation, partial pressure of arterial oxygen, and oxygen delivery were calculated.

Results: The unassisted SVC Glenn CI tended to be greater than the TCPC or IVC Glenn CI. Significant augmentation of total CI was achieved with mechanical assistance for SVC Glenn (109% ± 24%, $P = .04$) and TCPC (130% ± 109%, $P = .01$). The assisted CI achieved at least a mean baseline biventricular CI for all 3 support modes. Oxygen delivery was greatest for assisted SVC Glenn (1786 ± 1307 mL/L/min) and lowest for TCPC (1146 ± 386 mL/L/min), with a trend toward lower common atrial and pulmonary artery pressures for SVC Glenn.

Conclusions: SVC bidirectional Glenn circulation might allow optimal augmentation of the CI and oxygen delivery in a failing single ventricle using a conventional pediatric ventricular assist device. The results from our model also suggest that the Fontan circulation itself can be supported with systemic ventricular assistance of the single ventricle. (J Thorac Cardiovasc Surg 2014;147:1271-5)

Despite tremendous improvement in the outcomes of adult patients with ventricular assist devices (VADs),[1,2] the options for pediatric patients have continued to be limited. A failing single ventricle circulation imposes particular challenges to providing mechanical circulatory support.

Previous attempts to support the single ventricle circulation mechanically have suggested that a custom-built assist device is needed to push,[3-5] rather than pull, through the pulmonary circulation. We hypothesized that using a conventional VAD, with or without conversion of a total cavopulmonary connection to a bidirectional Glenn cavopulmonary connection, would allow assistance by pulling blood through the circuit and improve the cardiac index (CI).

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METHODS

The Animal Care and Use Committee of the Children's National Medical Center approved the study, and all animals received humane care in compliance with the "Guide for Care and Use of Laboratory Animals," published by the National Institutes of Health (Bethesda, Md).

Five 25-kg, naive Yorkshire swine (Archer Farms, Darlington, Md) were used for the present study. The pigs underwent percutaneous atrial septostomy at the National Institutes of Health, followed by surgical construction of univentricular cavopulmonary connection at the Children's National Medical Center.

Percutaneous Balloon Atrial Septostomy

The pigs were anesthetized with atropine, butorphanol, ketamine, and xylazine and maintained with isoflurane and mechanical ventilation.

Abbreviations and Acronyms

CI	= cardiac index
IVC	= inferior vena cava
IVC Glenn	= IVC cavopulmonary connection
MPA	= main pulmonary artery
PAP	= pulmonary artery pressure
SVC	= superior vena cava
SVC Glenn	= SVC cavopulmonary connection
TCPC	= total cavopulmonary Fontan connection
VAD	= ventricular assist device

Percutaneous arterial and venous access was obtained. If a patent foramen ovale was not present, a standard Mullins technique transseptal puncture was performed. The atrial septal communications were enlarged by inflation of large (18-20 mm in diameter) balloon angioplasty catheters. The experiments were guided by radiographic fluoroscopy (Siemens Medical, Erlangen, Germany) and intracardiac echocardiography (AcuNav; Biosense-Webster, Diamond Bar, Calif).

Surgical Creation of Univentricular Circulation

After premedication with intramuscular ketamine and xylazine, the anesthesia was maintained by a continuous intravenous infusion of fentanyl, midazolam, and pancuronium and mechanical ventilation.

Using a median sternotomy, after systemic heparinization and proximal ascending aortic and bicaval venous cannulation, normothermic cardiopulmonary bypass was established using a continuous flow pump (Rotaflow, Maquet Inc, Wayne, NJ) and membrane oxygenator (Terumo FX-15, Ann Arbor, Mich).

Using 2 limbs of 16-mm ePTFE (W. L. Gore & Associates, Inc, Flagstaff, Ariz) conduits in a Y configuration, the anatomic substrate to establish a cavopulmonary connection was created by construction of an end-to-side anastomosis of the graft limbs to the superior vena cava (SVC), inferior vena cava (IVC), and main pulmonary artery (MPA). With appropriate clamping of the limbs of the Y and snaring of the SVC, IVC, or MPA, a total cavopulmonary Fontan connection (TCPC), an SVC cavopulmonary connection (SVC Glenn), and an IVC cavopulmonary connection (IVC Glenn) could be established (Figure 1).

An ultrasonic flow probe (Veri Q; MediStim USA Inc, Plymouth, Minn) placed around the distal ascending aorta measured the cardiac output, which indexed to body surface area provided the CI. The superior caval venous cannula was removed and the inferior caval cannula moved to the right atrial appendage to drain the common atrium. By excluding the oxygenator and cardiotomy reservoir using a bypass line, the cardiopulmonary bypass circuit was converted to function as a continuous flow VAD. Pressure was monitored in the common atrium (using a catheter placed through the left atrial appendage) and in the cavopulmonary circuit using a pulmonary arterial catheter.

All the pigs were weaned off cardiopulmonary bypass to achieve baseline biventricular data. Each of the 3 study conditions (TCPC, SVC Glenn, and IVC Glenn) was created in random sequence in each pig. The endpoints were measured after achievement of steady state in each of the 3 conditions in their native state (unassisted) and when assisted by the continuous flow VAD (assisted). Although the flow measurements were available for all the pigs, the data required for calculation of tissue oxygen delivery were available for 3 pigs only.

At the end of the study, all the pigs were humanely killed.

Statistical Analysis

Continuous data are reported as the mean ± standard deviation. Paired *t* tests were used to compare the assisted and unassisted state for each of the 3 conditions. The statistical analyses were performed using IBM SPSS Statistics, version 19 (SPSS Inc, Chicago, Ill).

RESULTS

The baseline CI in the pigs after the surgical procedure with both limbs of the Y graft clamped was low (1221 ± 451 mL/m^2/min), suggesting the marginal status of their circulation after the extensive procedure. The CI was even lower in the unassisted state after appropriate clamp removal and placement for all 3 cavopulmonary connection conditions. However, it was higher for the SVC Glenn (1191 ± 747 mL/m^2/min) than for the TCPC (754 ± 357 mL/m^2/min) or IVC Glenn (781 ± 389 mL/m^2/min; Table 1 and Figure 2).

Significant augmentation of the total CI was achieved with mechanical assistance for each of the 3 conditions. A greater than twofold increase in the total CI was seen in all the 3 cavopulmonary conditions and was statistically significant for SVC Glenn (109% ± 24%, $P = .04$) and TCPC (130% ± 109%, $P = .01$; Table 1 and Figure 2). Assisted CI achieved at least a mean baseline biventricular CI for all 3 support modes. The amount of flow contribution to the total cardiac output from the VAD was 60% in SVC Glenn, 64% in IVC Glenn, and 76% in TCPC.

The common atrial pressure tended to be lower in the "assisted" state in all 3 conditions compared with that in the "unassisted" state (Table 1).

The mean pulmonary artery pressure was greater in all the 3 cavopulmonary connection conditions in the unassisted state than with the baseline biventricular circulation (baseline, 21.0 ± 13.6 mm Hg; SVC Glenn, 25.3 ± 4.6 mm Hg; IVC Glenn, 28.0 ± 4.9 mm Hg; TCPC, 27.8 ± 5.6 mm Hg). The mean pulmonary artery pressure (PAP) was lower in the assisted state than in the unassisted state in all 3 cavopulmonary connection conditions for 4 of the 5 study animals (Figure 3), resulting in a lower group mean PAP in the assisted state for all 3 conditions (Table 1). A paradoxical increase in the PAP was seen in 1 study animal.

The oxygen saturation and arterial oxygen tension (partial pressure of oxygen in arterial blood) decreased in both partial cavopulmonary connection conditions (SVC Glenn and IVC Glenn) in the assisted state compared with that in the unassisted state. However, the overall augmentation of the cardiac output offset the desaturation and resulted in greater oxygen delivery in the assisted state for both conditions. No decrease in oxygen saturation or arterial oxygen tension was seen from the unassisted to assisted state for TCPC. Oxygen delivery was greater in the assisted state for all 3 conditions and was greatest for assisted SVC Glenn (1786 ± 1307 mL/L/min) and lowest for TCPC (1146 ± 386 mL/L/min; Table 1).