CARDIOPULMONARY SUPPORT AND PHYSIOLOGY

THE INTRA-AORTIC CANNULA PUMP: A NOVEL ASSIST DEVICE FOR THE ACUTELY FAILING HEART

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Objective: The intra-aortic cannula pump is a catheter pump designed to support the acutely failing heart. It expels blood from the left ventricle into the ascending aorta in a pulsatile flow pattern. The aim of the study was to analyze the hemodynamic performance of this new intracardiac support system in acute heart failure. **Methods:** A 24F cannula was studied in a series of 16 sheep. Hemodynamic changes were assessed in the nonfailing, the moderately failing, and the severely failing heart. Heart failure was induced by an injection of microspheres into the left anterior descending coronary artery. The cannula was inserted through the aortic arch and introduced through the aortic valve into the left ventricle. **Results:** Cannula insertion was feasible in all animals. Flow through the intra-aortic cannula flow was increased to a maximum of 3 L/min. No hemodynamic changes were observed in the nonfailing heart. A significant increase in cardiac output was observed in the moderately and severely reduced left ventricle (2.67 ± 0.7 L to 3.51 ± 0.83 L; $P = .001$; and 1.18 ± 0.77 L to 2.43 ± 0.44 L; $P = .001$, respectively). A drop in left atrial pressure was achieved in moderate and severe heart failure (14.1 ± 5.93 mm Hg to 9.71 ± 2.63 mm Hg; $P = .0001$; and 23 ± 7.16 mm Hg to 11.2 ± 2.55 mm Hg; $P = 0.0001$, respectively). Systolic and diastolic systemic blood pressures increased in the severely failing heart (57.3 ± 12.8 mm Hg to 75.4 ± 11.2 mm Hg; $P = .0001$; and 35.6 ± 8.2 mm Hg to 60 ± 14.3 mm Hg; $P = .0006$, respectively). **Conclusions:** Hemodynamic data demonstrate the beneficial effects of the intra-aortic cannula pump in moderate and severe heart failure. The intra-aortic cannula pump represents a new modality for the treatment of acute heart failure. (J Thorac Cardiovasc Surg 1999;118:924-9)

Cardiogenic shock remains 1 of the leading causes of death in spite of major progression in cardiac surgery and cardiology.¹⁻³ Ventricular assist devices are generally used for the treatment of severe heart failure

when maximal pharmacologic support or the use of intra-aortic balloon pump counterpulsation is ineffective.⁴ A variety of left ventricular assist devices have been applied for the treatment of acute heart failure. These devices offer hope of the improvement of survival for patients with postcardiotomy cardiogenic shock.⁵⁻⁸ However, the application of these devices usually requires a surgical procedure and involves significant morbidity.⁹⁻¹¹

The intra-aortic cannula pump (IACP) is a catheter pump (Hemodynamics LTD, Upper Yoqneam, Israel) designed to support the failing heart by expelling blood in a pulsatile flow pattern from the left ventricle into the ascending aorta. It can be introduced by various approaches.

The aim of this study was to analyze the hemodynamic effects of this new intracardiac support system in a model of acute heart failure.

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Material and methods

Sixteen sheep, weighing 45 to 60 kg, were used in this study. All animals received humane care in compliance with the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources, National Research Council, and published by the National Academy Press, revised 1996.

Anesthesia. After a 36-hour food fasting period, all animals received premedication with 0.2 mg/kg body weight intramuscular atropine. General anesthesia was induced with 0.20 mg/kg intramuscular xylazine and 10 mg/kg intramuscular ketamine. To facilitate endotracheal intubation, a non-depolarizing muscle relaxant, intravenous atracurium 0.5 mg/kg, was used. Positive pressure ventilation (Harvard Apparatus Co, S Natick, Mass) was started (oxygen/room air mixture 1:1; halothane, 0.5% to 1.0%). Anesthesia was maintained with intravenous administration of fentanyl (0.02 mg/kg) and atracurium (0.5 mg/kg). Continuous electrocardiography was used for heart rate and rhythm recording.

Operative procedure and experimental protocol. After left thoracotomy was performed, the pericardium was opened and suspended. To prevent ventricular arrhythmia during manipulation of the heart, 100 mg of lidocaine HCl was given intravenously with the opening of the pericardial sac. A continuous infusion at a dose of 1 mg/kg per hour was started thereafter. Baseline activated clotting time was recorded, and heparin was administered intravenously at a dose of 300 IU/kg. Activated clotting time was maintained above 480 seconds throughout the procedure. Fluid manometer lines were inserted to the left atrium and femoral artery for hemodynamic measurements. Simultaneous monitoring was performed with an 8-channel recorder (Kipp & Zonen, Delft, The Netherlands). Continuous cardiac output monitoring was performed with an ultrasonic flow probe (Transonic Systems, Ithaca, NY) placed around the main pulmonary artery.

The IACP support system consists of a pulsatile pump and a disposable cannula-valve unit, which expels blood from the left ventricle into the ascending aorta (Fig 1). The device comprises (Fig 2) an electrohydraulic-driven piston that forces fluid into the disposable head, triggered by the electrocardiogram. The fluid displaces a polyurethane membrane, enabling a pulsatile blood flow through the cannula with a valve mechanism.¹² During the unloading phase (Fig 2, A), the blood is pumped from the tip of the catheter, through a 1-way valve, while the side holes in the aortic segment of the catheter are kept closed by another, opposite, 1-way valve. In the expelling phase (Fig 2, B), the tip valve is in the closed position, which expels blood only from the aortic side holes.

After surgical preparation of the aortic arch, the IACP was inserted, and the tip of the cannula was advanced to the left ventricular cavity. Tip positioning was verified by pressure measurement. IACP flow was gradually increased until maximal flow of 3.0 L was achieved and was recorded in different flow rates.

The induction of heart failure was performed by embolization¹³ of beads (Bangs Laboratories Inc, Fishers, Ind) into the left anterior descending coronary artery in repeated doses of 0.2 mL. Heart failure was defined as moderate when cardiac

Fig 1. The IACP is a catheter pump. It expels blood from the left ventricle into the ascending aorta in a pulsatile flow pattern.

output (CO) declined in increments of 25% to 50% related to baseline and as severe when the decrease in CO exceeded 50%.

Hemodynamic variables were recorded at baseline condition and during moderate and severe heart failure. All measurements were recorded with and without IACP support.

Statistics. The results are presented as mean $\pm$ SE. We created general linear models by the method of least squares to perform analysis of variance and covariance. We account for the fact that each of these 16 animals was studied at each of the 3 levels of heart failure by including animal designation in the linear model. For comparing a variable between different heart failure degrees, we computed the adjusted least squares mean of the variable at each heart failure degree. We computed the SE of the least square means. We used *t* tests for comparing between the LSM. Computations were performed by SAS 6.12 software (SAS/STAT User's guide Version 6; SAS Institute Inc, Cary, NC).

Results

The hemodynamic condition of all animals was stable during the baseline phase. Induction of moderate and severe heart was successfully accomplished. All animals survived the study protocol. No inotropic support was given during the entire procedure. In the preliminary series, we used a tube graft sutured to the aor-

Fig 2. Schematic cross-section of the IACP. **A**, Unloading phase. **B**, Expelling phase. The IACP consists of a pulsatile pump and a disposable cannula-valve unit. It comprises an electrohydraulic driven piston that forces fluid into the head (triggered by electrocardiogram [ECG]) and displaces a polyurethane membrane, enabling a pulsatile blood flow through the cannula with a valve mechanism.

Table I. Hemodynamic variables at baseline condition and after induction of heart failure

	Baseline	Moderate heart failure	Severe heart failure
CO (L/min)	3.5 ± 0.8	2.6 ± 0.4*	1.2 ± 0.4*
Systolic ABP (mm Hg)	96.1 ± 24.8	84 ± 24.4	57.3 ± 14.6*
Diastolic ABP (mm Hg)	73.3 ± 25.6	58.2 ± 23.6*	35.1 ± 3.6*
LAP (mm Hg)	10.6 ± 5.2	14.1 ± 6*	23.2 ± 7.6*

All values are presented as mean ± SD.

* $P < .001$.

tic side and inserted the cannula through it. Later, we found this method unnecessary because of the reasonable size of the cannula as compared with the aorta and introduced it in a direct fashion. Passing the device through the aortic valve was feasible in all cases. However, in some cases, a slight pressure on the aortic root was required to facilitate the insertion. No damage to the aortic valve leaflets was observed.

Left ventricular and aortic pressures were measured during catheter insertion and after correct positioning in the left ventricle with no transvalvular gradient. The

catheter did not cause any aortic incompetence as measured by left ventricular end-diastolic pressures before and after its positioning. During catheter operation, left ventricular end-diastolic negative pressures were measured subsequent to the device pumping mechanism.

Blood loss was minimal without the need for blood transfusions. Table I summarizes the hemodynamic variables at baseline condition and after induction of heart failure.

Once moderate heart failure was induced; a significant decrease in CO, diastolic arterial blood pressure (ABP) as well as an increase in left atrial pressure (LAP) was noted (26%, $P < .001$; 21%, $P < .001$; 33%, $P < .001$, respectively). During severe heart failure CO further declined in 66% related to baseline ($P < .001$). A reduction in systolic and diastolic ABP in 40% ($P < .001$) and 52% ($P < .001$), respectively, was observed, with a concomitant 130% increase in LAP ($P < .001$).

During IACP activation, a significant increase in CO was observed both in moderate and severe heart failure. Fig 3 demonstrates a linear model of the increase in CO related to IACP flow. Maximal IACP assist up to $236\% \pm 69\%$ was achieved in severe heart failure ($P < .001$).

Systolic and diastolic ABP increased significantly by

Fig 3. Linear model presents the change in CO that is related to IACP flow at baseline, moderate, and severe heart failure. A significant increase in CO was observed both in moderate and severe heart failure ($P < .01$). Data are shown as the mean $\pm$ the SE of the least squares mean.

Fig 4. Linear model presents the change in diastolic ABP that is related to IACP flow at baseline, moderate, and severe heart failure. Diastolic ABP increased significantly ($P < .001$) only in the severely failing heart and in flow rates over 1.5 L/min. Data are shown as the mean $\pm$ SEM.

the IACP only in the severely failing heart and in flow rates over 1.5 L/min (Fig 4) to a maximum of $51\% \pm 15\%$ and $73\% \pm 11\%$, respectively ($P < .001$).

IACP activation caused a significant decrease in left atrial pressure both in moderate and severe heart failure (Fig 5).

Discussion

Heart failure, whether acute or chronic, is associated with poor prognosis and limited life expectancy.^{14,15} In severe cases of acute heart failure, the mortality rate can exceed 85%.¹⁶ The immediate treatment modalities available to patients with cardiogenic shock are limited. Once medical therapy and intra-aortic balloon pumping

are found to be insufficient, ventricular assist devices are usually necessary. The two major indications for the application of ventricular assist devices are postcardiotomy cardiogenic shock and acute myocardial infarction.

A myocardial infarction model with intracoronary injection of microspheres was chosen for cardiac failure induction, because of its simplicity and the controlled, staged failure that it achieves. In this study, we used the IACP, a catheter pump that can deliver pulsatile blood flow at a rate exceeding 3 L/min. The application of the IACP rapidly unloads the left ventricle, as evidenced by a significant reduction in left atrial pressure. The IACP increases diastolic arterial blood pressure, thus aug-

Fig 5. Linear model presents the change in LAP that is related to IACP flow. A significant decrease ($P < .001$) in LAP was recorded both in moderate and severe heart failure. Data are shown as the mean $\pm$ SEM.

menting coronary perfusion. Furthermore, use of the IACP may contribute to myocardial recovery by reducing ventricular wall tension and consequently decreasing the oxygen requirement.^{17,18} These favorable effects may lead to infarct size limitation¹⁹ and protect against further ischemia by minimizing the unfavorable redistribution of coronary blood flow.²⁰

The IACP effect was maximal during severe heart failure because of the relatively high contribution of the device to CO. Although the hemodynamic benefits of transaortic flow pumping are well established,²¹ the use of a pulsatile catheter pump in this application is novel. Despite the fact that pulsatile versus nonpulsatile perfusion is a topic of continuing controversy, it is acknowledged that the benefits of pulsatile perfusion are mainly manifested in high-risk patients.²² The advantage of pulsating flow is its similarity to normal physiologic conditions. As such, it ameliorates whole body inflammatory response and maintains normal organ function, producing flow and mean intravascular pressure rates that are lower than those produced with nonpulsatile flow.^{23,24}

In preliminary safety studies, no evidence of hemolysis was observed that was associated with the operation of this device. The IACP can be inserted directly into the aorta or its major tributaries without the need to anastomose a tube graft, rendering the procedure less traumatic. Correct tip positioning is accomplished by pressure monitoring, thus eliminating the need for fluoroscopy or echocardiography.

This type of cannula produced a maximum of 3 L/min, a flow that could not be sufficient to permit a total substitution of a failing heart. The device described is not designed as a total artificial left heart. The select-

ed 24F cannula is an optimization between medium-sized catheter diameter and subsequent flow capacity limitation but minimizes surgical complexities. To achieve a higher flow, a larger cannula can be introduced through the same approach or by apical insertion.

The IACP, designed as a short-term circulatory support system, is intended mainly as a bridge to myocardial recovery. This system can be easily replaced by another device to provide long-term assistance, in the event that such myocardial recovery does not occur.

In this study, we demonstrated the beneficial hemodynamic effect of a pulsatile 24F IACP cannula in an animal model of cardiac failure as the result of myocardial ischemia. Several limitations of this 24F catheter pump were noted. Maximal flow is limited below the native CO. It can be used as an assist and not as a substitute device. For further clinical use, a transfemoral insertion will be attractive but will require minimization of catheter diameter.

Additional studies are needed to investigate the application of this new device in other failure conditions.

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