Copulsion Balloon for Right Ventricular Assistance
Preliminary Trials

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Background—Options for management of acute right ventricular (RV) failure are limited. This report describes preliminary testing of a temporary RV assist device that acts by direct compression of the RV. The system comprises a pancake-shaped silicone balloon (5 cm diameter) connected to a drive console that delivers a 65-mL pneumatic pulse during cardiac systole.

Methods and Results—Initial in vivo tests were performed on 6 pigs (weight, 41±4 kg). RV wall motion and stroke volume were monitored via transesophageal echocardiography. Acute RV failure was created by graded right coronary ligation, which yielded a 63% reduction in RV stroke volume (39.9±8.2 to 14.7±1.9 mL; P<0.002). We secured the balloon over the RV free wall by attaching it to the edges of the opened pericardium. The sternum was then reapproximated, and data were collected with the device off and on (every beat). Device placement had no deleterious effect on RV function. Balloon activation returned RV stroke volumes to normal (37.8±9.2 mL) and increased mean pulmonary artery pressures from 13±2 to 16±3 mm Hg (P<0.01). RV compression did not induce or exacerbate tricuspid regurgitation. Mean aortic pressure improved from postinfarction levels but did not return to normal.

Conclusions—We conclude that the pulmonary circulation can be supported in the short term via cardiac compression and that balloon copulsation techniques for short-term RV failure should be tested in long-term models. (Circulation. 1999;99:2815-2818.)

Key Words: heart-assist device ■ hemodynamics ■ balloon ■ heart failure ■ ventricles

Right ventricular (RV) failure is a life-threatening condition with a variety of causes and limited treatment options. Clinical disorders known to induce RV failure include isolated RV infarction, septal dyskinesis, pulmonary disease, and inferior wall myocardial infarction. The most common cause of long-term RV failure is chronic pulmonary hypertension secondary to congestive left-heart failure.1,2 Acute RV failure is a significant risk factor for cardiac transplant recipients and occurs in 20% to 30% of patients receiving left ventricular (LV) assistance as a bridge to cardiac transplantation. Moreover, acute RV dysfunction often complicates efforts to provide circulatory support after postcardiotomy cardiogenic shock.3–5

When pharmacological agents are unable to improve RV function, surgeons must rely on mechanical means to restore blood flow to the pulmonary circulation and LV. Current options for mechanical assistance include centrifugal pumps, positive displacement pumps, and right-sided diastolic counterpulsation. The drawback common to all these mechanisms is that they require invasive, time-consuming procedures to secure requisite cannulae and/or anastomoses to the pulmonary artery, unlike the intra-aortic balloon pump, which can be positioned and retracted through a femoral artery cutdown. Hence, development of a quick and simple means to support the pulmonary circulation during periods of transient RV dysfunction is needed.

This report describes preliminary trials of an RV copulsion balloon (RVCB) designed to effect right-heart assistance via direct cardiac compression. The primary purpose of this study is to determine whether significant RV support can be achieved via pneumatic actuation of a balloon placed between the sternum and the RV. The ultimate objective is to develop a simplified RV assist device that can be inserted and removed as readily as an intra-aortic balloon pump.

Methods

RV Copulsion Balloon

The RV copulsion device comprises a pancake-shaped silicone balloon attached to a pneumatic driveline (Figure 1). A patch of Teflon felt is secured to the underside of the balloon by a silicone-based adhesive (Silastic brand 7–2947, Dow Corning) for purposes of device anchoring. Standard intra-aortic balloon pump (IABP) driveline tubing is secured to the balloon sidewall port (1.5 cm OD) via a straight 3/8-in to 1/2-in connector. The connector is fitted with a rigid domed mesh to reduce wall stresses at the connector-balloon interface. All attachment sites are pneumatically sealed with UV-curable adhesive (Loctite model 3311).

Unstressed, the balloon measures roughly 5 cm in diameter and 2 cm in height and occupies a volume of 40 mL. Because of its high compliance, however, balloon volumes can be readily expanded to twice this value without damage. Two lateral convolutions allow the balloon to lay flat under negative pressures, provide a smooth surface for RV compression, and maximize active diastolic filling.
Pneumatic Drive System

Device actuation is controlled via a commercial IABP pump console (System 83, Datascope Corp) modified to deliver a predetermined volume of helium gas to the balloon during cardiac systole. To meet RV copulsation requirements, a second safety chamber was connected in parallel with the original (Figure 2) to double driver volume capacity to 65 mL. Cardiac synchronization is achieved by setting the driver inflation delay switch to the “out” position, thereby disabling the automatic delay function and allowing balloon inflation to occur immediately after detection of the QRS complex. Apart from these 2 alterations, drive-console operating conditions are identical for both RV copulsation and aortic counterpulsation.

Experimental Procedure

The operative procedures described below were performed in compliance with the “Guide for the Care and Use of Laboratory Animals” prepared by the National Academy of Sciences and published by the National Institutes of Health (NIH publication 86-23, revised 1985). In addition, this project was approved by the Allegheny-Singer Institutional Animal Care and Use Committee.

Six female pigs (weight, 35 to 45 kg) were used to determine the feasibility of supporting RV function via pneumatic actuation of a balloon placed between the RV and the sternum. Each animal was sedated with intramuscular injections of ketamine (615 mg) and xylazine hydrochloride (80 mg) before induction of general anesthesia. Anesthesia was maintained with 1% to 2% isoflurane delivered through an endotracheal tube. A Swan-Ganz catheter and arterial pressure line were placed via the external jugular vein and carotid artery, respectively. The chest was entered through a median sternotomy, and 3 additional pressure lines were placed directly into the left atrium and both ventricles. RV stroke volume was calculated based on Doppler velocity profiles measured across the pulmonary valve via transesophageal echocardiography (TEE).

Acute RV failure was induced by graded right coronary artery ligation. RV dysfunction was considered significant when a 50% reduction in stroke volume was observed. Bretylium tosylate (50 mg), procainamide hydrochloride (600 mg), and lidocaine (160 mg/h) were administered to prevent arrhythmias. The RVCB was subsequently placed over the heart so that the (empty) balloon was sandwiched between the RV free wall and Teflon backing. The device was secured in place by suturing the Teflon backing to the edges of the opened pericardium. The sternum was then reapproximated in preparation for RVCB activation. Balloon inflation was timed to begin on detection of the QRS complex, whereas the deflation point was adjusted manually to coincide with cardiac diastole (based on RV and balloon pressure waveforms).

Hemodynamic data were collected under 4 conditions: before RV infarction (baseline); after RV infarction and before balloon placement (postinfarction); after balloon placement with the device inactive (balloon off); and after balloon placement with the device inflated with every heartbeat (balloon on). RVCB driveline pressures were also recorded during intervals of cardiac assist. RV copulsation was continued for periods up to 30 minutes. On completion of the study, all animals were euthanized with 20 mEq of KCl while they remained under general anesthesia.

Data Collection and Statistical Analysis

Data were collected under closed-chest conditions to mimic physiological conditions anticipated during clinical application of a catheter-based RVCB. Pressure and ECG waveforms were digitized at a rate of 100 samples/s for periods of 1 to 2 minutes and stored in an IBM PS/2 personal computer (data acquisition package: CODAS, Datag Instruments). Data sets were collected on establishment of steady-state hemodynamics for each condition tested (defined as stable arterial pressures maintained for $\geq 30$ seconds). These data were processed with XANALYZE, a comprehensive cardiovascular waveform analysis program. Data sets comprising 10 contiguous heartbeats were isolated and the waveforms averaged to minimize spurious results. Repeated-measures ANOVA was performed (TRUE EPISTAT, Epistat Services) to determine the significance of differences between treatment groups. A 2-sided $P$ value of $<0.05$ was considered statistically significant. All summary data are expressed as mean $\pm$ SD.

Results

Induction of RV Failure Via Coronary Occlusion

Graded right coronary occlusion produced significant RV dysfunction, yielding a 23% decrease in peak RV pressures, a 97% increase in end-diastolic RV pressures, and a 63% reduction in RV stroke volumes relative to preinfarction baseline measurements (Table 1). Systolic and diastolic arterial pressures were also reduced by 36% and 37%, respectively, whereas heart rate fell from $92 \pm 12$ to $76 \pm 8$ bpm ($P<0.002$).

Impact of Device Placement on Cardiac Function

Placement of the RVCB over the RV free wall and reapproximation of the sternum had no significant effect on cardiac function, as evidenced by hemodynamic measurements taken after infarction (before device insertion) and after insertion with the balloon deflated (Table 1). Furthermore, TEE revealed no evidence of cardiac compression after device fixation.
Hemodynamic Response to Device Activation

RVCB activation produced marked increases in right-heart pressures and flows, restoring these parameters to near-normal (preinfarction) levels (Table 1). RV and pulmonary artery systolic pressures increased 69% and 56%, respectively, over postinfarction baseline, whereas RV diastolic pressures were lowered by 30% (Figure 3). RV stroke volumes increased dramatically from 14.7 ± 2.5 mL to 37.8 ± 9.2 mL (P < 0.005), and mean pulmonary artery pressures improved from 12.7 ± 2.4 to 15.8 ± 2.9 mm Hg (P < 0.01). Systolic arterial pressures were also markedly improved with balloon activation, increasing from 66.3 ± 11.6 to 78.8 ± 8.7 mm Hg (P < 0.02), but did not return to preinfarction levels (103.7 ± 10.5 mm Hg). Heart rate remained unchanged from the postinfarction baseline rate of 76 bpm, and no significant cardiac arrhythmias were noted.

Substantial displacement of the RV free wall toward the ventricular septum was observed via TEE during balloon inflation. Doppler measurements across the pulmonary outflow tract showed increased blood flow velocity during RV ejection (Table 2). Similar measurements made across the tricuspid valve revealed that RV compression did not induce or exacerbate regurgitation.

Discussion

RV failure is a condition that frequently ends in disastrous clinical outcome. Currently, there is little that can be easily done to support the RV during periods of transient dysfunction. Ventricular assist devices are commonly used to support the circulation during both right- and left-heart failure. This, however, is a cumbersome undertaking that requires extensive materials and considerable manpower support, which is not readily available to all centers. The purpose of the RVCB is to provide a relatively inexpensive means to support the pulmonary circulation that can be quickly and easily implemented in the acute setting.

To date, there are no reports in the literature regarding deployment of a copulsating balloon in the anterior mediastinum to assist RV function. Several groups, however, have proposed the use of dynamic cardiac compression as a possible means to aid the failing heart and have tested these techniques in animals. These studies suggest that external forces can be safely applied to the epicardial surface of the heart to improve contractile efficiency and cardiac output. Reports published by Anstadt et al describe a method of direct mechanical ventricular actuation (DMVA) that involves placement of a contoured cup over both ventricles. The cup is implanted through a left thoracotomy, is held in place by a slight vacuum introduced between the heart and rigid housing, and uses positive and negative pneumatic pressures to expand and deflate a flexible diaphragm that

**TABLE 1. Hemodynamic Effects of Device Placement and Activation**

<table>
<thead>
<tr>
<th></th>
<th>RV Pressure, mm Hg</th>
<th>PA Pressure, mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HR, bpm</td>
<td>Systolic</td>
</tr>
<tr>
<td>Baseline</td>
<td>91.7 ± 12.1*</td>
<td>28.0 ± 5.3*</td>
</tr>
<tr>
<td>Postinfarction</td>
<td>75.8 ± 7.6</td>
<td>21.5 ± 4.7</td>
</tr>
<tr>
<td>Balloon off</td>
<td>74.7 ± 9.7</td>
<td>22.8 ± 5.5</td>
</tr>
<tr>
<td>Balloon on</td>
<td>75.8 ± 9.6</td>
<td>36.5 ± 2.1*</td>
</tr>
</tbody>
</table>

HR indicates heart rate; RVSV, RV stroke volume; and PA, pulmonary artery.

Values are mean ± SD; n = 6 animals for all measurements except RVSV (n = 5).

*Significantly different from postinfarction group (P < 0.05).

**TABLE 2. Pulmonary Artery Dimensions and Stroke Distance Calculations Based on Doppler TEE Measurements**

<table>
<thead>
<tr>
<th>PAD, cm</th>
<th>Pig 1</th>
<th>Pig 2</th>
<th>Pig 3</th>
<th>Pig 4</th>
<th>Pig 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time velocity integral, cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>9.10</td>
<td>9.98</td>
<td>11.30</td>
<td>12.87</td>
<td>11.56</td>
</tr>
<tr>
<td>Postinfarction</td>
<td>4.14</td>
<td>4.23</td>
<td>3.50</td>
<td>4.30</td>
<td>4.22</td>
</tr>
<tr>
<td>Balloon off</td>
<td>2.84</td>
<td>2.75</td>
<td>2.44</td>
<td>3.59</td>
<td>5.66</td>
</tr>
<tr>
<td>Balloon on</td>
<td>7.80</td>
<td>8.50</td>
<td>10.24</td>
<td>10.38</td>
<td>13.00</td>
</tr>
</tbody>
</table>

PAD indicates pulmonary artery diameter.

Stroke volume is determined by multiplying time velocity integral by pulmonary artery cross-sectional area (πr^2).

Figure 3. Pressure waveforms recorded during RV copulsation and immediately after balloon deactivation. RV and pulmonary artery systolic pressures are increased significantly during balloon inflation, whereas minimum RV diastolic pressures are reduced during active deflation. Balloon inflation is triggered immediately on QRS detection, and the deflation point is adjusted to optimize pulmonary blood flow.
encircles the heart. DMVA has proven quite effective in that total cardiac support has been achieved during ventricular fibrillation for periods up to 7 days. Still, despite significant advantages over conventional assist schemes (eg, no cannulation or blood-contacting parts), this technique is limited to those cases in which extremely invasive measures and extensive surgical resources can be brought to bear.

The ultimate goal of this research is to develop an inexpensive, catheter-based RV assist device that can be deployed and retrieved with the ease of an intra-aortic balloon pump. This article describes our first step toward this objective: that is, a pilot study designed to determine whether significant RV support can be achieved via timed inflation and deflation of a balloon placed between the sternum and the heart.

Our data show that balloon copulsation can significantly increase pulmonary artery pressures and restore RV stroke volume to normal levels during periods of severe RV dysfunction. In these experiments, however, postinfarction bradycardia served to limit total cardiac output to 78% of baseline under assist conditions (versus 30% without balloon augmentation). The use of temporary atrioventricular sequential pacing may therefore be warranted in bradycardic patients to normalize heart rate and further improve cardiac output.

Benefits to LV function were also observed as a result of RV copulsation, most likely owing to increased blood flow to the LV combined with displacement of the septum toward the LV during balloon inflation. Placement of the balloon between the RV free wall and sternum had no significant impact on cardiac function, and gross examination yielded no evidence of damage to the epicardial surface after brief (30-minute) periods of support.

**Experimental Limitations**

The use of Doppler echocardiography to calculate RV stroke volume can be considered a drawback owing to potential inaccuracies caused by beam misalignment, errors in vessel cross-sectional area estimates, and assumptions of laminar flow, constant flow area, and uniform flow velocity across the vessel. Baseline calculations nevertheless yielded mean stroke volumes (40 mL) and cardiac outputs (3.65 L/min) commensurate with values expected in 41-kg pigs, which suggests that these measurements were indeed reasonably accurate. Moreover, Doppler echocardiography is considered a very reliable technique for assessing percent changes in stroke volume owing to uniform measuring conditions within each experiment. Given the uniformity and consistency of these pulmonary flow measurements, it is reasonable to conclude that these stroke volume calculations reflect actual changes due to RV ischemia and copulsation assistance.

These data were collected under short-term circulatory assist conditions and therefore do not provide information regarding long-term use. Rather, this study was designed to determine the feasibility of RV balloon copulsation from a biomechanical perspective. Results from these preliminary trials indicate that this technique is a mechanically viable means of supporting the pulmonary circulation. Whether balloon copulsation can be successfully used to effect long-term RV support has yet to be determined.

**Conclusions**

We conclude that this method of cardiac copulsation is an effective means of providing short-term RV assistance and that additional studies are warranted. Future work will involve the development and manufacture of a catheter-mounted copulsation balloon and custom-designed drive unit suitable for human use. In vivo testing will be performed in a model of short-term RV infarction and will mimic the proposed clinical method of device placement. The duration of support will be significantly extended, and histological examinations of the RV will be performed to determine whether prolonged cardiac compression leads to significant myocardial damage. These trials, if successful, would confirm the efficacy of minimally invasive RV copulsation and bring this technology closer to clinical implementation.

**Acknowledgments**

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**References**
