

A Miniature Right Heart Support System Improves Cardiac Output and Stroke Volume during Beating Heart Posterior/Lateral Coronary Artery Bypass Grafting

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ABSTRACT

Background: Certain heart manipulations carried out to access anastomotic sites during beating heart coronary artery bypass (OPCAB) compromise hemodynamics, and these risks can affect end-organ perfusion and limit patient selection. Evidence suggests that right heart support (RHS) augments left ventricular preload and provides hemodynamic stability. This study evaluated hemodynamic measures in OPCAB with RHS with respect to individual target vessels and general target distribution groups.

Methods: Beating heart surgery was performed on 52 patients with left ventricular preload managed with RHS. The average patient age was 69.9 years, and the average ejection fraction was 42.9% ± 10.9%. Measurements of cardiac output, stroke volume, mean arterial pressure (MAP), heart rate, and cardiac index (CI) were taken at baseline, during each anastomosis with the optimal heart position, and when the RHS was momentarily interrupted prior to heart release. Anastomoses were categorized individually and into posterior/lateral (n = 91) or anterior/right (n = 90) groups and divided into the following output groups based on CI with optimal heart positioning without RHS: group 1 (low output; CI < 1.8), group 2 (marginal output; 1.8 ≤ CI < 2.2), group 3 (acceptable output; CI ≥ 2.2), and group 4 (output unchanged or increased).

Results: One hundred eighty-one vessels were grafted with an average of 3.5 per patient. Significant reductions in CI, MAP, and stroke volume were observed for all target vessels when RHS was briefly off, especially for posterior and lateral target vessels (12%-26% decrease). In both posterior/lateral and anterior/right target vessel groups, RHS improved CI and MAP in ≥90% of the anastomoses (groups 1-3). Without RHS, 60% of posterior/lateral and 54% of anterior/right target positions resulted in critically low or marginal output (groups 1 and 2). There was one bypass conversion and no surgical interruptions, intraoperative intra-aortic balloon pump placements, or deaths.

Conclusion: Augmenting left ventricular preload with RHS improves hemodynamic measures during OPCAB for all target vessel positions and provides critical support in a large number of anastomoses.

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INTRODUCTION

Beating heart surgery for coronary revascularization continues to evolve and is gaining in popularity. The advantages of this approach have been well documented in the literature and include reduced costs, decreased blood transfusions, reduced inflammatory response, and lower morbidity and mortality [Ascione 2000, Demaria 2002]. Off-pump coronary artery bypass (OPCAB) grafting is technically more challenging, and the initial experience was with single- or two-vessel disease. Advances in techniques of wall stabilization and heart displacement are resulting in increasing numbers of multivessel procedures in patients with higher-risk factors [Murkin 2002].

One of the potential difficulties with OPCAB is hemodynamic instability as a consequence of positioning the heart to gain optimal anastomotic access. This instability has singularly added increased complexity to intraoperative monitoring and pharmacologic management [Heames 2002]. Some commonly employed techniques for maintaining hemodynamic parameter values include steep Trendelenburg positioning, fluid loading, and inotropic administration. The need for pharmacologic support in OPCAB may be quite high. Recent studies report that vasopressors were required during 80% of anastomoses of diagonal arteries, 66% of anastomoses of left anterior descending arteries, 47% of anastomoses of obtuse marginal (OM) arteries, and 40% of anastomoses of right coronary and posterior descending arteries (PDA), even with routine use of Trendelenburg positioning [Do 2002].

Evidence suggests that the cause of hemodynamic deterioration is impaired diastolic filling of the right heart [Mathison 2000]. Compromised right ventricular filling is a direct consequence of ventricular compression rather than impaired contractility or ischemia. Right heart support (RHS) has recently been shown to augment the left ventricular preload and provide hemodynamic stability [Lima 2001]. This study evaluated hemodynamic measures in OPCAB with RHS with respect to individual target vessel positions and target distributions to determine which and how many anastomotic positions were vulnerable to hemodynamic deterioration and to quantitate the hemodynamic effect in the absence of RHS.

Table 1. Patient Characteristics*

Patients, n	52
Average age (range), y	69.9 (46-100)
Male/female sex	84%/16%
NYHA class	
I	9%
II	17%
III	28%
IV	48%
Ejection fraction	42.9% ± 10.9%
≤30%, n	9/46 (19.6%)
Family history CAD, n	26/50 (52.0%)
Previous MI, n	25/50 (50.0%)
Diabetes treatment, n	25/50 (50.0%)
Hypercholesterolemia, n	41/50 (82.0%)
Renal failure, n	5/48 (10.4%)
Arrhythmia, n	10/49 (20.4%)
Previous CAB, n	0
Previous valve, n	0
Anastomoses, n	181
Average/patient, n	3.5
Vessel distribution, n	
Circumflex	8
OM-1	30
PDA	29
OM-2	20
Diagonal	27
RCA	13
LAD	50
Ramus	3
OM-3	1
Procedure status	
Elective	24.0%
Urgent	66.0%
Emergent	10.0%
Mean pump flow, L/min	
Circumflex	2.03 ± 0.70
OM-1	2.48 ± 0.61
PDA	2.10 ± 0.70
OM-2	2.44 ± 0.56
Diagonal	2.13 ± 0.72
RCA	2.49 ± 0.76
LAD	1.90 ± 0.60

*NYHA indicates New York Heart Association; CAD, coronary artery disease; MI, myocardial infarction; CAB, coronary artery bypass; OM-1, first obtuse marginal coronary artery; PDA, posterior descending coronary artery; RCA, right coronary artery; LAD, left anterior descending coronary artery.

METHODS

In a prospective study, 52 patients underwent multivessel OPCAB surgery with left ventricular preload managed with RHS (A-Med Systems, West Sacramento, CA, USA). Eligibility included all patients who were candidates for primary coronary artery bypass grafting (CABG) with beating heart surgery involving at least one posterior or lateral target vessel; all participating patients gave their consent. Preoperative demographic and risk variable data were collected. Operative procedural data included pump flow rates in liters per minute, the target vessel, conversion to cardiopulmonary bypass, intra-aortic balloon pump placement, intraoperative adverse events, postoperative left ventricular assist device placement, and intraoperative death.

RHS was performed as previously described [Lima 2001]. Positioning and stabilization devices and techniques were used as needed. Target vessels were the circumflex or OM arteries (first, second, third), the left or right PDA, the left anterior descending artery, the diagonal artery, the ramus, and the main right coronary artery. Cardiac output, mean arterial pressure (MAP), heart rate, stroke volume, and cardiac index (CI) data were obtained at baseline prior to initiating RHS (cardiac output, 4.97 ± 1.7 L/min; MAP, 69.5 ± 12.0 mm Hg; heart rate, 77.2 ± 17.2 beats/min; stroke volume, 66.2 ± 22.8 mL; CI, 2.43 ± 0.9 L/min per m^2), during each anastomosis on RHS with the heart optimally positioned (n = 181), and when RHS was off for 1 minute prior to heart release. Continuous cardiac output monitoring was performed with the PulseCO System (LiDCO, Cambridge, UK) with calibration by thermodilution. Target vessel anastomoses were categorized individually or into posterior/lateral (n = 91) or anterior/right (n = 90) categories and divided into the following groups based on the CI with optimal positioning and RHS momentarily off: group 1 (low output, CI < 1.8), group 2 (marginal output, 1.8 ≤ CI < 2.2), group 3 (acceptable output, CI ≥ 2.2), and group 4 (output unchanged or increased).

Continuous data are presented as the mean ± standard deviation and as ranges, and categorical data are presented as the percentage. Comparisons of on-pump and off-pump parameters by target vessel were made with paired *t* tests. Intraoperative baseline measurements were used to confirm hemodynamic stability prior to RHS. The study period was from the beginning to the end of the operative procedure.

RESULTS

Demographic, risk variable, and operative data are summarized in Table 1. In 52 patients, 181 grafts were performed with an average of 3.5 grafts per patient (range, 2-4 grafts). The mean patient age was 69.9 years, and the mean preoperative ejection fraction was 42.9% (range, 20%-65%). Seventy-six percent of the cases were considered urgent or emergent, 76% were in New York Heart Association class III/IV, and 19.6% of patients had an ejection fraction of less than 30%. Six of 48 patients (12.5%) had prophylactic preoperative intra-aortic balloon pump placement. The mean RHS pump flow rate ranged from 1.90 to 2.49 L/min.

As shown in Table 2, there was a significant decrease in CI, MAP, and stroke volume for all individual target vessel distributions when the heart was optimally positioned and RHS was momentarily off. Hemodynamic deterioration was greater in the circumflex, OM-1, OM-2, and PDA vessel distributions, with a decrease in CI ranging from 14% to 26%. There was no significant change in heart rate in any target vessel group (data not shown).

Table 2. Hemodynamic Changes for Each Target Vessel with Right Heart Support (RHS) Off and the Heart Optimally Positioned*

Target Vessel (n)	Measure	RHS On	RHS Off	Decrease, %	*P*
Circumflex (8)	CI	2.72 ± 0.81	2.24 ± 0.96	19.3	.021
	MAP	75.0 ± 11.1	62.5 ± 9.4	15.8	.015
	SV	60.2 ± 21.8	47.0 ± 21.5	20.1	.022
OM-1 (30)	CI	2.48 ± 0.67	1.87 ± 0.69	25.8	<.001
	MAP	71.1 ± 9.5	58.5 ± 12.1	17.5	<.001
	SV	61.6 ± 19.0	47.1 ± 19.4	25.1	<.001
PDA (29)	CI	2.46 ± 0.76	1.96 ± 0.74	19.7	<.001
	MAP	70.3 ± 12.5	59.4 ± 12.5	14.9	<.001
	SV	59.5 ± 23.0	48.8 ± 22.8	18.3	<.001
OM-2 (20)	CI	2.40 ± 0.65	2.00 ± 0.50	14.3	.0014
	MAP	68.9 ± 16.9	60.9 ± 17.6	11.8	<.001
	SV	60.5 ± 21.3	51.5 ± 17.8	13.3	<.001
Diagonal (27)	CI	2.45 ± 0.80	2.11 ± 0.71	13.7	<.001
	MAP	68.4 ± 12.3	63.6 ± 11.7	6.9	<.001
	SV	69.2 ± 29.3	58.5 ± 25.4	14.6	<.001
RCA (13)	CI	2.52 ± 0.87	2.15 ± 0.91	14.9	.015
	MAP	67.7 ± 11.1	61.3 ± 14.3	9.6	.020
	SV	68.2 ± 26.5	56.8 ± 24.1	17.0	.008
LAD (50)	CI	2.33 ± 0.67	2.02 ± 0.70	12.9	<.001
	MAP	68.7 ± 9.7	62.7 ± 10.1	8.3	<.001
	SV	62.6 ± 21.3	53.3 ± 21.3	14.9	<.001

*Values are presented as the mean ± SD, and *P* values represent the results of paired *t* tests. Units of measure are as follows: cardiac index (CI), L/min per m^2; stroke volume (SV), mL; mean arterial pressure (MAP), mm Hg. Other abbreviations are expanded in the footnote to Table 1.

CI and MAP were evaluated in terms of posterior/lateral (n = 91) and anterior/right (n = 90) target vessel categories within CI groups to quantitate the number of anastomotic sites with hemodynamic deterioration and the values of the decreases. Tables 3 and 4 show that there were significant decreases in CI and MAP in 94.4% of the anterior/lateral and 90.0% of the anterior/right anastomotic positions when RHS was off. Only 6 of 91 posterior/lateral and 9 of 90 anterior/right anastomotic positions did not benefit from RHS. In 60% of the anterior/lateral and 54% of the posterior/right anastomotic sites, momentarily stopping RHS resulted in a low (CI < 1.8) or marginal output (1.8 ≤ CI < 2.2). A MAP value of less than 60 mm Hg with RHS off occurred in 60% of the posterior/lateral and 34% of the anterior/right target vessels. The low CI group (CI < 1.8) experienced the greatest decrease in CI and MAP with RHS off. Similarly, the posterior/lateral target vessels had a greater hemodynamic decrease without RHS than the anterior/right sites.

In this series of patients, there was one conversion to cardiopulmonary bypass, no intraoperative or postoperative intraaortic balloon pump or ventricular assist device placements, and no intraoperative adverse events. All patients underwent complete revascularization, and there were no patient deaths.

DISCUSSION

The potential advantages of RHS during OPCAB are beginning to emerge. These advantages include hemodynamic maintenance, improved organ perfusion, improved visualization and surgical access, decreased use of inotropes, improved technical ease and anesthesia management, increased incidence of multivessel OPCAB, inflammatory responses and outcomes equivalent to OPCAB without RHS, decreased periods of stabilization and operative time, increased frequency of patient selection for OPCAB, and a higher frequency of complete revascularization [Lima 2001, Caputo 2002, Sharony 2002]. Most notable is the ability to provide hemodynamic stability. Some studies suggest that heart manipulations associated with accessing posterior and inferior target vessels cause significant hemodynamic instability, whereas others show more significant deterioration with anterior target sites [Do 2002]. The present study confirms that without RHS there is significant deterioration in hemodynamic parameter values during OPCAB in all target vessel positions and in most anastomoses.

Variability was noted in individual anastomotic sites in the present series. Some hemodynamic measures changed dramatically when RHS was momentarily off, whereas others appeared minimally affected. Thus, a more detailed evaluation was undertaken. All anastomoses were divided into posterior/lateral or anterior/right target vessel groups and further categorized into CI groups on the basis of the measured CI when RHS was momentarily off. The changes in CI and MAP were evaluated as an indication of which target distributions were vulnerable to hemodynamic deterioration, how many target positionings would result in low or marginal output, and how much the output declined. The results show that both posterior/lateral and anterior/right are affected in

Table 3. Changes in Cardiac Index by Cardiac Index Group in Posterior/Lateral and Anterior/Right Target Vessels*

Cardiac Index Group	% of Total	RHS On, L/min per m^2	RHS Off, L/min per m^2	Decrease, %	*P*
Posterior/lateral (n = 91)					
Low (CI < 1.8)	41.8	2.02 ± 0.49	1.35 ± 0.35	31.9	<.0001
Marginal (1.8 ≤ CI < 2.2)	18.7	2.43 ± 0.32	1.97 ± 0.10	17.9	<.0001
Acceptable (CI ≥ 2.2)	33.0	3.20 ± 0.55	2.68 ± 0.48	15.8	<.0001
Unchanged or increased	6.6	2.06 ± 0.57	2.44 ± 0.38	−22.8	.039
Anterior/right (n = 90)					
Low (CI < 1.8)	34.3	1.83 ± 0.39	1.36 ± 0.36	24.8	<.0001
Marginal (1.8 ≤ CI < 2.2)	20.0	2.34 ± 0.23	2.01 ± 0.12	13.7	<.0001
Acceptable (CI ≥ 2.2)	35.6	3.08 ± 0.60	2.67 ± 0.49	12.7	<.0001
Unchanged or increased	10.0	2.03 ± 0.82	2.47 ± 0.93	−23.8	.017

*Data are presented as the mean ± SD, and *P* values represent the results of paired *t* tests. RHS indicates right heart support; CI, cardiac index.

≥90% of anastomoses. A greater proportion of the posterior/lateral anastomotic positions experienced a critically low, clinically significant CI (<1.8) without RHS (41.8% versus 34.3%). The lower the output, the greater the percentage decrease in CI and MAP without RHS. This finding suggests that RHS may be particularly indicated in patients with low or marginal output at the beginning of OPCAB.

Although the absolute decline in the hemodynamic parameters was not large in some anastomotic positions, it should be noted that the off-pump measurements were obtained during a very brief period when the pump was stopped and just before the heart was released. It is unknown how far these measurements might have decreased with the heart in optimal positioning but without right heart circulatory support. In studies of animals, where such determinations are possible, heart displacement has resulted in large changes in hemodynamic measures [Porat 2000].

Patient selection for OPCAB is not well defined. It has been suggested that the only absolute preoperative contraindications to OPCAB are CABG with valve replacement, major arrhythmias, and cardiac insufficiency [Lima 2002]. Other studies have shown independent risk factors for mortality and morbidity are operations related to the circumflex and right coronary artery branches, recent myocardial infarction, female sex, and acute arrhythmias, results suggesting relative contraindications for OPCAB [Lund 2001]. In reality, patients are often excluded from OPCAB if they have multivessel disease, if the circumflex, PDA, or ramus is involved, or if they otherwise have high-risk conditions [Murkin 2002]. It should be noted that a large proportion of the patients in this study had higher-risk variables. The procedures were multivessel (an average of 3.5 grafts/patient), and 76% of the cases were urgent or emergent. Seventy-six percent of the patients were in NYHA III/IV, 20% had arrhythmias, 50% had prior myocardial infarctions, and 20% had an ejection fraction of ≤30%. Although this study did not evaluate risk factors, it does indicate a wide application of OPCAB in multivessel disease. More studies are needed to determine the specific patient populations and characteristics that most benefit from OPCAB with RHS.

The use of RHS during OPCAB is a matter of preference at present. Surgical preference may be given to fluid and pressor management instead of mechanical support for hemodynamic problems or for patients with difficult access or too many target vessels. Concern for hemodynamic stability may exclude some patients from consideration for OPCAB. The use of inotropes and pressor agents may have untoward consequences, because they increase cardiac workload and myocardial oxygen consumption and promote vasoconstriction and acidosis. Unfortunately, it is unknown which patients will require which interventions to stabilize hemodynamic param-

Table 4. Changes in Mean Arterial Pressure by Cardiac Index Group in Posterior/Lateral and Anterior/Right Target Vessels*

Cardiac Index Group	% of Total	RHS On, mm Hg	RHS Off, mm Hg	Decrease, %	*P*
Posterior/Lateral (n = 91)					
Low (CI < 1.8)	41.8	69.5 ± 9.8	53.6 ± 10.5	22.3	<.0001
Marginal (1.8 ≤ CI < 2.2)	18.7	68.3 ± 8.8	59.0 ± 9.8	13.6	<.0001
Acceptable (CI ≥ 2.2)	33.0	73.7 ± 12.3	65.7 ± 10.4	10.4	<.0001
Unchanged or increased	6.6	71.9 ± 30.6	72.7 ± 25.5	−3.1	NS
Anterior/Right (n = 90)					
Low (CI < 1.8)	34.3	66.5 ± 10.7	58.6 ± 12.3	11.9	<.0001
Marginal (1.8 ≤ CI < 2.2)	20.0	69.5 ± 0.2	62.8 ± 7.7	9.3	<.0001
Acceptable (CI ≥ 2.2)	35.6	71.2 ± 10.5	65.8 ± 10.9	7.5	<.0001
Unchanged or increased	10.0	63.4 ± 10.9	66.6 ± 10.3	−5.6	.076

*Data are presented as the mean ± SD, and *P* values represent the results of paired *t* tests. RHS indicates right heart support; CI, cardiac index; NS, not significant.

eter values during OPCAB. This study suggests that RHS provides a method that can eliminate this unknown.

CONCLUSION

OPCAB with RHS is a safe and effective method for providing hemodynamic stability and is appropriate to use in multivessel CABG. This study shows that both posterior/lateral and anterior/right target anastomoses benefit, with the greatest effect being in posterior/lateral distributions. In addition, a large proportion of anastomotic positions result in critically low or marginal output without RHS. CI and percent decrease with RHS momentarily off are inversely related. We conclude that OPCAB with RHS can potentially increase the frequency of patient selection for OPCAB and that RHS represents an improvement in surgical management.

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