Mechanisms of hemodynamic changes during off-pump coronary artery bypass surgery

[Les mécanismes de changements hémodynamiques pendant le pontage aortocoronarien à cœur battant]

Pierre Couture MD FRCPC,* André Denault MD FRCPC,* Patrick Limoges MD FRCPC,* Peter Sheridan MD FRCPC,* Denis Babin MSc,* Raymond Cartier MD FRCSC†

Purpose: To describe the mechanisms of hemodynamic changes during off-pump coronary artery bypass graft surgery (OP-CABG).

Source: Pertinent medical literature in the English and French languages was identified through a Medline computerized literature search and a manual search of selected articles, using off-pump coronary artery surgery, beating heart surgery, hemodynamic, and transesophageal echocardiography as key words. Human and animal studies were included.

Principal finding: Hemodynamic variations in OP-CABG may be due to mobilization and stabilization of the heart, or myocardial ischemia occurring during coronary occlusion. Suction type and compression type stabilizers produce hemodynamic effects through different mechanisms. Heart dislocation (90° anterior displacement) and compression of the right ventricle to a greater extent than the left ventricle are responsible for hemodynamic alterations when using suction type stabilizers. Compression of the left ventricular outflow tract and abnormal diastolic expansion secondary to direct deformation of the left ventricular geometry are proposed mechanisms for hemodynamic derangements with compression type stabilizer. Coronary occlusion during the anastomosis can have additional effects on left ventricular function, depending on the status of collateral flow. The value and limitations of electrocardiographic (ECG), hemodynamic and echocardiographic monitoring modalities during OP-CABG are reviewed.

Conclusions: In summary, hemodynamic changes which can either be secondary to the stabilization technique or to transient ischemia represent an important diagnostic challenge during off-bypass procedures. The mechanism can vary according to the stabilization system. Current monitoring such as ECG and hemodynamic monitoring are used but remain limited in establishing the cause of hemodynamic instability. Transesophageal echocardiography is used in selected patients to diagnose the etiology of hemodynamic instability and can direct therapy, particularly in those with severe myocardial systolic and diastolic dysfunction, mild to moderate mitral regurgitation, or for patients who are unstable during the procedure.

Objectif : *Décrire les mécanismes de changements hémodynamiques pendant le pontage aortocoronarien (PAC-CB).*

Source : *La documentation pertinente en anglais et en français a été trouvée par la consultation de Medline et par une recherche manuelle dans des articles sélectionnés, en utilisant les mots-clefs suivants : off-pump coronary artery surgery, beating heart surgery, hemodynamic, et transesophageal echocardiography. Nous avons inclus les études sur les humains et les animaux.*

Constatations principales : *Les variations hémodynamiques pendant le PAC-CB peuvent être causées par la mobilisation et la stabilisation du cœur ou l'ischémie myocardique survenant pendant l'occlusion d'une artère coronaire. Les stabilisateurs de type aspiration et compression produisent des effets hémodynamiques par des mécanismes différents. La bascule cardiaque (déplacement antérieur de 90°) et la compression du ventricule droit, plus grande que celle du ventricule gauche, sont responsables des modifications hémodynamiques avec le stabilisateur de type aspiration. La compression de la voie d'éjection du ventricule gauche et l'expansion diastolique anormale secondaire à une déformation directe de la géométrie ventriculaire gauche sont les mécanismes de changements hémodynamiques proposés avec le stabilisateur compressif. L'occlusion coronaire pendant l'anastomose peut avoir d'autres effets sur la fonction ventriculaire gauche selon l'état du débit collatéral. La valeur et les limites des modalités du monitorage électrocardiographique (ECG), hémody-*

From the Departments of Anesthesiology,* and Surgery,† Montreal Heart Institute, Montreal, Quebec, Canada.

Address correspondence to: Dr. Pierre Couture, Department of Anesthesiology, Montreal Heart Institute, 5000 Bélanger Street East, Montreal, Quebec H1T 1C8, Canada. Phone: 514-376-3330, ext. 3732; Fax: 514-376-1355; E-mail: p.couture@sympatico.ca

Accepted for publication January 4, 2002.
Revision accepted June 10, 2002.

namique et échocardiographique pendant le PAC-CB ont été réexaminées.

Conclusion : *En résumé, les changements hémodynamiques qui peuvent être, soit secondaires à la technique de stabilisation, soit à l'ischémie transitoire, représentent un défi diagnostique important pendant les interventions à cœur battant. Le mécanisme peut varier selon le système de stabilisation. Le monitorage courant comme l'ECG et le monitorage hémodynamique sont utilisés, mais demeurent limités pour définir la cause de l'instabilité hémodynamique. L'échocardiographie transœsophagienne est utilisée chez des patients choisis pour diagnostiquer l'étiologie de l'instabilité hémodynamique et peut orienter le traitement, surtout chez ceux qui présentent une dysfonction systolique et diastolique sévères, une régurgitation mitrale faible ou modérée et chez les patients dont l'état est instable pendant l'intervention.*

CORONARY artery bypass grafting on the beating heart has become a widely applied procedure. Although off-pump coronary artery bypass grafting (OP-CABG) procedures are quite attractive because of the obvious advantages of avoiding cardiopulmonary bypass-related complications, the main limitations of this approach to surgery are incomplete revascularization and intraoperative hemodynamic instability.

The basic principles of complete revascularization should not be compromised when considering OP-CABG.[1] Indeed, in a review of 3372 surgical patients from the Coronary Artery Surgery Study Registry with triple-vessel disease, patients with severe angina (New York Heart Association class III and IV) or left ventricular (LV) dysfunction (ejection fraction < 35%) had a better six-year survival and event-free survival when grafts to three or more vessels were completed.[2] However, with off-pump procedures, there has often been a compromise in the completeness of revascularization, with many authors reporting an ungrafted circumflex coronary artery (CX).[3] Tasdemir *et al.*[4] identified ungrafted CX stenoses as a risk factor for morbidity and mortality. In order to obtain adequate exposure for complete revascularization, particularly for the difficult lateral CX and posterior branches, midline sternotomy, combined with methods providing appropriate positioning of the heart and adequate mechanical stabilization, remains the most popular approach for OP-CABG.[1,5,6]

The second problem related to CABG, which is the topic of this review, is hemodynamic instability. Hemodynamic variations in OP-CABG may be due to mobilization and stabilization of the heart, or myocardial ischemia occurring during coronary occlusion. Each type of stabilization device can also produce its own related hemodynamic effects. The purpose of this article is to review the mechanisms of hemodynamic derangements according to the stabilization device used.

Methodology

Pertinent medical literature in the English and French languages was identified through a Medline computerized literature search and a manual search of selected articles, using off-pump coronary artery surgery, beating heart surgery, hemodynamic, and transesophageal echocardiography (TEE) as key words. Human and animal studies were included. The Medline search was updated up to January 2002 and references included in this review. In addition, the experience of the Montreal Heart Institute in OP-CABG surgery since 1996 is described.

Results

Using the above strategy, a total of 80 articles were retrieved. References selected are representative but not all- inclusive. A total of 39 references were excluded because they were not specifically related to the topic. We will also discuss the value and limitations of electrocardiographic, hemodynamic and echocardiographic monitoring modalities during OP-CABG.

Discussion

Hemodynamic changes during OP-CABG: peculiarities of the stabilization device

Various devices are being marketed for the purpose of restricting regional wall motion: the Diamond Grip Rib Spreader Cardiac Stabilizer (Genzyme Corp., Cambridge, MA, USA), the Origin Cardiac Stabilizer and Stabilizer Foot (Origin, Menlo Park, CA, USA), Mechanical Stabilizer (CTS Inc., Cupertino, CA, USA), the Octopus Tissue Stabilizer System (Octopus, Medtronic Inc., Minneapolis, MN, USA), and the fork-type compression stabilizer developed and currently used at the Montreal Heart Institute (CoroNéo Inc., Montreal, Quebec, Canada).[1,7-9] While these devices are different, their stabilizing effects could generally be attributed to a compression effect (CoroNéo Inc., CTS Inc., Cupertino, CA, USA) or to a suction effect (Octopus, Medtronic Inc., Minneapolis, MN, USA).[10]

1) SUCTION TYPE STABILIZER (OCTOPUS, MEDTRONIC INC.)

Hemodynamic variations occurring during OP-CABG using the Octopus stabilizer have been first studied in animals. Borst *et al.*[10] in Utrecht, The Netherlands, developed a mechanical suction stabilization system (Octopus, Medtronic Inc., Minneapolis, MN, USA)

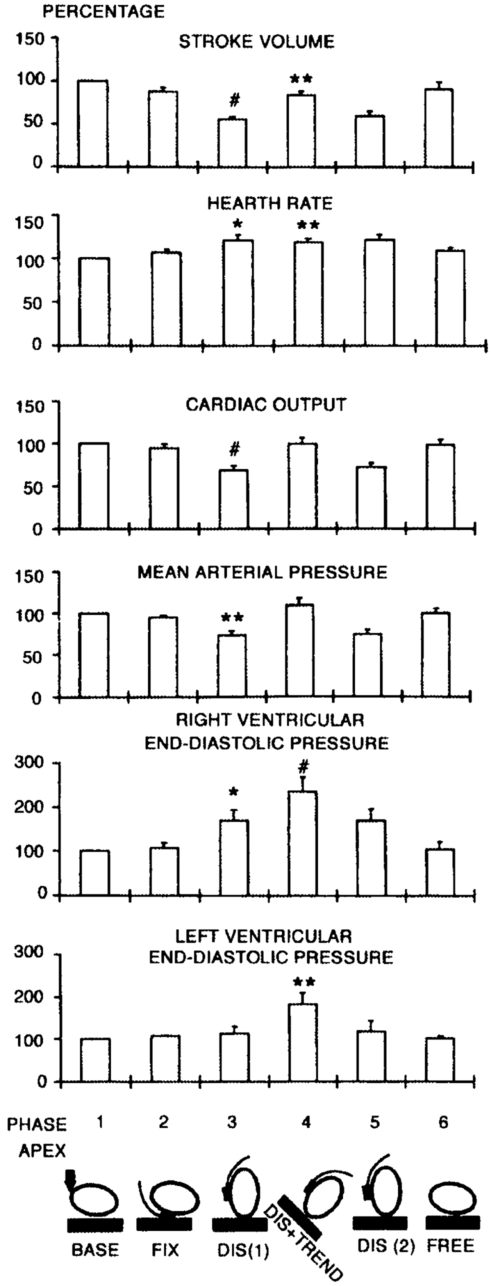

FIGURE 1 Relative changes in hemodynamic variables during vertical displacement of the beating porcine heart by the Utrecht Octopus and the effect of head-down tilt phase 1 (BASE) = pericardial control position; phase 2 (FIX) = fixation of the suction tentacles to the posterior cardiac wall; phase 3 [DIS (1)] = displacement of the heart by the Octopus, phase 4 (DIS + TREND) = Trendelenburg maneuver (20 head-down tilt); phase 5 [DIS (2)] = retracted heart with table returned to horizontal position; and phase 6 (FREE) = pericardial position after release of the Octopus. Statistical comparison with control values: $*P < 0.05$, $**P < 0.001$. *Reprinted with permission from the Society of Thoracic Surgeons (The Annals of Thoracic surgery, 1997; 63: S90).*

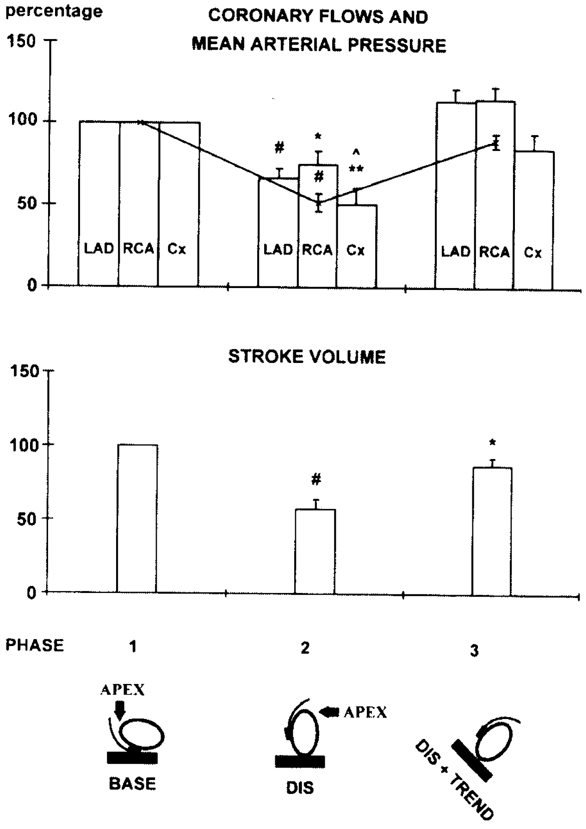

FIGURE 2 Relative changes in hemodynamic variables during vertical displacement of the beating porcine heart by the Medtronic Octopus stabilizer and the effect of the head-down tilt. Phase 1 (BASE) = pericardial control position; CX = circumflex coronary artery; phase 2 (DIS) = displacement of the heart by the Octopus; phase 3 (DIS + TREND) = Trendelenburg maneuver (20 head-down tilt) while the heart remained 90 retracted; LAD = left anterior descending coronary artery; RCA = right coronary artery; X = mean arterial pressure. Statistical comparison with control values $*P < 0.05$, $**P < 0.01$, $\#P < 0.001$, $^\wedge P < 0.046$ *vs* combined relative value of LAD and RCA flows. *Reprinted with permission from the Society of Thoracic Surgeons (The Annals of Thoracic surgery, 1998; 65: 1350).*

and, using the pig as a laboratory model, were able to show minimal arrhythmogenesis, no hemodynamic deterioration, little superficial histologic change related to suction application, and excellent reproducible reduction of cardiac surface motion to 1 mm by 1 mm. Although Borst *et al.*[10] found no hemodynamic deterioration with this device during grafting of the left anterior descending (LAD) artery and right coronary (RC) artery in a pig model, the main challenge in OP-CABG remains access to the CX territory.

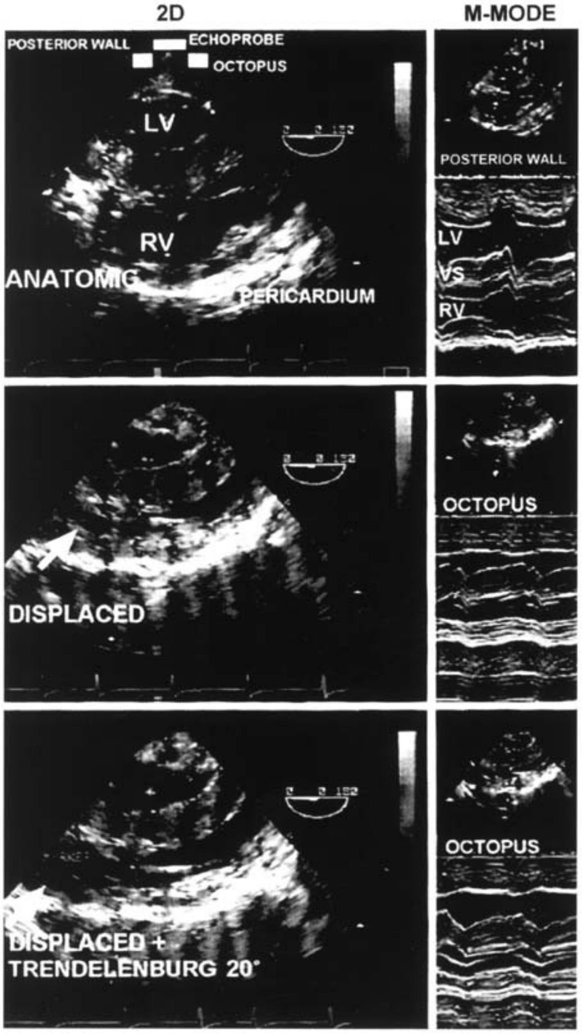

FIGURE 3 Echographic cross-sectional areas (left panels) and M-mode images (right panels) obtained during 90 anterior displacement (DISPLACED) and subsequent head-down positioning (+ TRENDELENBURG). VS = ventricular septum; RV = right ventricle; LV = left ventricle. The ultrasound probe was positioned between two Octopus tentacles and aligned to the posterior wall (ANATOMIC). Note the severe deformation of the RV on cardiac retraction (arrows, DISPLACED) and the partial recovery of RV cross-sectional area after the Trendelenburg maneuver. *Reproduced from reference 14 with permission.*

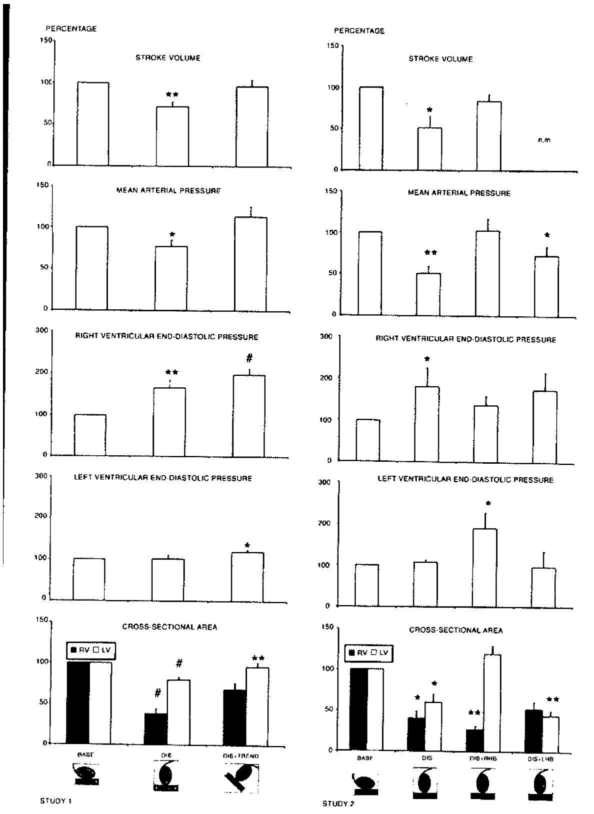

FIGURE 4 Relative changes in hemodynamic variables and RV and LV cross-sectional areas during vertical displacement of the beating porcine heart with Octopus tissue stabilizer (study 1) and the effect of mechanical circulatory support on displacement (study 2). Statistical comparison with control values $*P < 0.05$; $**P < 0.01$; $\#P < 0.001$; n.m. = not measured; erroneous readings from the ultrasound aortic flow probe caused by turbulent flow from LHB cannula. DIS = displaced; LV = left ventricle; RV = right ventricle; RHB = right heart bypass; LHB = left heart bypass. The measurements were taken during the following periods: study 1: BASE = pericardial control position; DIS = displacement of the heart by the Octopus; DIS + TREND = Trendelenburg maneuver while the heart remained retracted. In study 2, additional measurement periods included: DIS + RHB = heart displaced by the Octopus and supported with RHB and DIS + LHB = heart displaced and supported by LHB. *Reproduced from reference 14 with permission.*

Exposing posterior branches by displacing the beating heart (apex points anteriorly) tends to decrease arterial pressure both in the pig model[11] and in patients.[12] Experimentally, Grundeman,[11] and Jansen *et al.*[12] have reported the feasibility of immobilizing the posterolateral cardiac wall with the straight Octopus paddle fixed directly on the ventricle. The apex was progressively raised anteriorly during a two-minute period by pulling on the left ventricle. The heart "dislocation" (phase 3 of Figure 1) caused a 26% decrease in mean arterial pressure, a 37% decrease in cardiac output, biventricular failure characterized by a major drop in stroke volume (44%), despite elevation of right ventricular (RV) end-diastolic pressure and unchanged

TABLE I Hemodynamic changes during immobilization and presentation of target vessel by the Octopus tissue stabilizer

	Limited access		*Full access*	
	Anterior wall (n = 49)	*Anterior wall (n = 39)*	*Inferior wall (n = 32)*	*Posterior wall (n = 12)*
Heart rate (beats·min^{-1})				
Before Octopus	66 ± 11	65 ± 12	69 ± 12	66 ± 12
During Octopus	70 ± 11	75 ± 14	74 ± 14	77 ± 11
After Octopus	70 ± 12	72 ± 13	74 ± 13	77 ± 12
Mean arterial pressure (mmHg)				
Before Octopus	72 ± 9	74 ± 11	72 ± 11	73 ± 13
During Octopus	70 ± 11	70 ± 12	67 ± 10	66 ± 15
After Octopus	70 ± 11	69 ± 10	68 ± 8	60 ± 15
Cardiac index (L·min^{-1}·m^{-2})				
Before Octopus	3.3 ± 1.1	2.6 ± 0.5	2.9 ± 0.6	2.8 ± 0.6
During Octopus	3.1 ± 0.9	2.5 ± 0.4	2.6 ± 0.6	2.8 ± 0.5
After Octopus	3.1 ± 0.9	2.6 ± 0.4	2.5 ± 0.5	3.1 ± 0.7
Dopamine required				
During Octopus (%)	7 (14)	9 (23)	10 (31)	8 (67)

Data are mean ± standard deviation. Data of subxiphoid and left posterior access group not included. *Reproduced with permission from reference 18.*

LV end-diastolic pressure (Figure 1). Twenty degrees head-down position (Trendelenburg) normalized cardiac output and mean arterial pressure (phase 4 of Figure 1). There was also a decrease in coronary blood flow measured by ultrasound flow probe in the LAD artery, the RC artery, and the CX artery by 34%, 25% and 50% respectively, which was restored at 20 head down tilt (Figure 2).[13] Using the same experimental model,[14] these authors further elucidate the mechanism of the biventricular dysfunction by measuring RV and LV dimension with two-dimensional echocardiography (Figure 3). They observed that a significant portion of the RV free wall was pressed against the interventricular septum, whereas the RV outflow tract was somewhat narrowed but remained patent, resulting in a decrease in the RV dimension with a smaller decrease in LV dimension. No valvular incompetence was observed. Tilting the whole-body head down in 20 Trendelenburg position normalized mean arterial pressure, stroke volume, LV dimension, while it partially corrected RV dimension (Figure 4, study 1). In addition, right heart bypass increased stroke volume and mean arterial pressure by increasing LV preload, in contrast, LV bypass failed to restore systemic circulation (Figure 4, study 2). They concluded that the changes accompanying 90 anterior displacement of the beating porcine heart were caused primarily by RV deformation and decreased pump function without signs of valvular incompetence or inflow or outflow obstruction. The displacement prevented normal RV and LV diastolic expansion by pressing the heart against the surrounding tissue, resulting in RV diastolic dysfunction. It is inferred that vertical displacement affects mostly the RV function because the right heart bypass restored LV function whereas left heart bypass failed to restore cardiac output and mean arterial pressure.[14] These data are in agreement with a similar protocol using a sheep model[15] where right heart ventricular bypass also restored LV function.

This device has also been used successfully for multiple vessel OP-CABG in human studies[12,16,17] with minimal morbidity and mortality. Hemodynamic changes have been less well characterized in humans than in animal models using this device. Jansen *et al.* have reported their results on the first 100 patients with the Octopus stabilizer.[18] They observed that through a median sternotomy, exposure of the anterior wall and inferior wall is well tolerated hemodynamically (Table I). Exposure of the posterior wall is also well tolerated, provided that heart dislocation is performed slowly (approximately one minute; Table I). However, fluid redistribution (Trendelenburg manoeuver) and dopamine were necessary in 67% of patients to maintain arterial pressure with posterior wall exposure. Recently, Nierich *et al.*[17] showed in a study conducted on 150 patients that the stroke volume was mainly affected during diagonal (DIAG) revascularization (-25%). This was attributed to right heart compression, which is squeezed between the left ventricle and right pericardium.

More recently, Mathison *et al.* provided the first detailed clinical report during OP-CABG using the Octopus II.[19] Circumflex positioning resulted in a decrease in mean arterial pressure of 22.2 ± 4.4% and

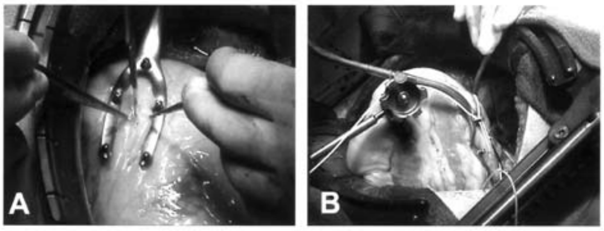

FIGURE 5 Example of the stabilizing system (Cor-Vasc System; CoroNéo Inc., Montreal, Quebec, Canada) used at the Montreal Heart Institute for the left anterior descending artery (A) and the marginal artery anastomosis (B).

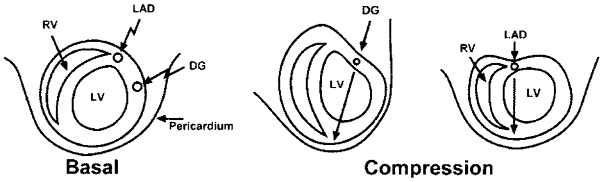

FIGURE 6 Schematic representation of the heart compression for the left anterior descending and diagonal coronary revascularization during beating heart coronary artery bypass graft surgery. DG = diagonal artery; LAD = left anterior descending artery; LV = left ventricle; RV = right ventricle. *Reproduced from reference 25 with permission.*

stroke volume of 28.5 ± 3.5%, an increase in left and right atrial pressure of 59.9 ± 15.9% and 166.7 ± 34.2%, and LV and RV end-diastolic pressure of 59.4 ± 16.6% and 151.4 ± 9.8%. Positioning for the posterior descending artery also resulted in a decrease in stroke volume of 22.4 ± 7.9% with an increase in left and right atrial pressure and RV end-diastolic pressure, with no significant change in LV end-diastolic pressure. Positioning for the left descending artery anastomosis showed the least hemodynamic change, although they observed a decrease in stroke volume of 17.5 ± 5.1% with an increase in right atrial and RV end-diastolic pressure. Using TEE, they observed that, for every positioning, the right ventricle is more affected by the compression, because its wall is thinner, its pressure is relatively low, and it is pressed against the pericardial cradle. Therefore, even if the left ventricle is compressed, the effect on the right ventricle is greater. They also explained that the increases in left and right atrial pressure were related to the anterior positioning of the heart, with the apex pointing upward, by the folding of the heart somewhere close to the atrioventricular valves, causing some flow obstruction. The same authors also have shown that RV assistance provided stable hemodynamic during exposure of the posterior wall.[20] Other authors have found LV assist devices to be effective in patients with LV failure.[21]

From these observations in animals and in humans, it appears that hemodynamic changes are primarily caused by changing the normal position of the heart, particularly with dislocation (90 anterior displacement) of the heart and compression of the right ventricle to a greater extent than the left ventricle. The Octopus system, when positioned on the anterior surface of the heart, suspends the anterior wall and does not seem to impede LV diastolic filling, although right heart compression can occur.[17] This is in contrast with access to the obtuse marginal and distal RC artery branch access, which may lead to diastolic filling abnormalities of the heart. This is thought to be secondary to the Octopus articulating arms and tissue stabilizers which immobilize the heart by pressure, instead of suspension.

Finally, coronary occlusion during the anastomosis can have other effects on LV function, and these effects depend on collateral flow.[22] Brown *et al.* showed that occlusion of a severely stenosed vessel (> 90%) with good collaterals may lead to a less severe myocardial ischemia than the occlusion of a vessel with only a 60 to 70% stenosis with less collateral flow.[23] Koh *et al.*[22] using intraoperative TEE in patients undergoing OP-CABG, observed that both LV systolic and diastolic function were depressed in those patients without collaterals compared to only diastolic dysfunction in patients with collaterals during coronary occlusion of the LAD artery lasting up to 15 min using the Octopus device. All disturbances normalized within ten minutes of reperfusion. However, the hemodynamic consequences of the displacement of the heart to facilitate the procedure are probably not influenced by the degree of coronary artery stenosis.[24]

2) compression type stabilizer (the fork-type compression stabilizer) [CoroNéo Inc., Montreal, Quebec, Canada]

At the Montreal Heart Institute, OP-CABG surgery began in September 1996.[9] Our experience with beating heart surgery now includes close to 740 cases and represents over 2100 distal anastomoses.[9] The conversion rate to cardiopulmonary bypass is 0.4% (Dr. R. Cartier, personal communication). Based on the first 500 patients, an average of 3.10 grafts/patient were com-

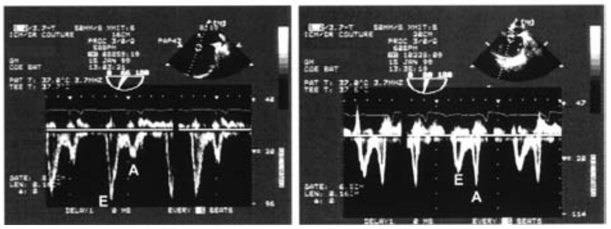

FIGURE 7 The effect of clamping the diagonal artery on the mitral E and A wave. The occlusion of the diagonal was associated with a reduction of the E velocity with an increase in the A velocity compatible with ischemia or preload reduction through compression of the LV outflow tract.

pleted and 72% of the patients had either triple, quadruple or quintuple bypass.[9] The CX artery was grafted in 73% of cases; in 7%, two grafts were completed on the CX network. The detailed surgical technique has been published[1] but in summary, all surgeries were performed with a full median sternotomy. Anesthesia technique was left to the discretion of the attending anesthesiologist. Phenylephrine and nitroglycerine infusions were administered as required to normalize hemodynamics. Target artery immobilization was achieved through mechanical stabilization with a specifically designed surgical apparatus capable of ergonomically accessing all coronary arteries (Cor-Vasc system; CoroNéo Inc., Montreal, Quebec, Canada; Figure 5). A light-weight titanium retractor serves as the platform for this system. The system consists of four distinct coronary stabilizers, "push" (Figure 5A) and "pull" (Figure 5B) types, each optimized for specific artery exposure and immobilization. A bloodless surgical field is ensured by silastic bands (Retract-O-Tape; Quest, Allen, TX, USA), which isolate and occlude the target artery at the arteriotomy site. A heart "verticalizing" technique, was developed to expose the posterior circumflex territory through pericardial traction.[1] Four deep pericardial sutures are placed at the base of the heart, interspersed in a fan-shape arrangement between the left superior pulmonary vein and the inferior vena cava. The "verticalizing" technique enables extraction of the apex, with minimal distortion of the ventricle while preserving hemodynamics. The surgical table, rotated rightward (30) and set in Trendelenburg position, assists in exposing the posterior coronary territory and helps maintain RV preload. The coronary artery was stabilized using a pull type stabilizer. Exposure of the LAD and DIAG coronary arteries used the same setting except two traction sutures were usually used and the table was positioned in a reverse Trendelenburg position.

The hemodynamic changes associated with the use of this stabilizing system have been reported recently by Do and Cartier[25] in 31 patients undergoing OP-CABG monitored with a Swan-Ganz catheter (n = 25) or an Oximetric catheter (n = 6). The target coronaries were clamped proximally and distally to the anastomosis site without preconditioning. They observed a decrease in mean systemic arterial pressure (SAP) during the procedure, which differed according to the grafted coronary artery: LAD (-11 ± 19%), DIAG (-13 ± 27%), CX (-19 ± 17%) and RC or posterior descending artery (PDA; -17 ± 14%). The mean pulmonary artery pressure (PAP) increase was maximal with the DIAG (+47 ± 84%) and was more important during LAD (+30 ± 36%) and CX (+21 ± 48%) than RC/PDA revascularization (+10 ± 24%). There was no significant change in mixed venous oxygen saturation (SvO_2). These changes occurred during the stabilization period before vessel occlusion, and were well tolerated by all patients, in whom inotropic support was rarely needed. They concluded that using a "fork-type" stabilizer, the mobilization and stabilization of the heart were responsible for a decrease in SAP and an increase in PAP, rather than clamping of the coronary. The marked elevation in PAP during revascularization of the DIAG and LAD territory may be explained by a compression of the LV outflow tract, as illustrated in Figure 6. To further define the hemodynamic changes associated with the use of this "fork-type" stabilizer, we studied an additional 53 patients undergoing OP-CABG, in whom we also measured the cardiac output and SvO_2.[26] TEE was used in five of these patients to assess the systolic and diastolic function, to detect regional wall motion abnormalities and mitral regurgitation during the procedure. The left ventricle was divided in 16 segments according to the recommendation of the American Society of Echocardiography.[27] Mitral inflow velocities were measured at the tip of the mitral leaflets on three consecutive heartbeats at the end of expiration. The parameters recorded were the following: peak velocity of the early diastolic filling wave (E), late diastolic filling wave (A), and a ratio of these two velocities (E/A). Our results are in agreement with those reported earlier.[25] The SAP decrease was found after stabilization of the LAD (-8.6 ± 22.1%), DIAG (-14 ± 25.2%), CX (-16.3 ± 13.8%) and RC (-15.1 ± 15.6%). The anteroposterior compression of the beating heart was responsible for the most important changes in PAP. Indeed, PAP increase was only significant during DIAG (+37.7 ± 73.6%) and was more important on LAD (+23.9 ± 35.2%) than CX (+12.5 ± 35.9%) or RC revascularization (+12.7 ± 23.8%). Changes in SvO_2 were < 10% and the decrease

TABLE II Left ventricular dimensions and function from intraoperative transesophageal echocardiography minimally during invasive direct coronary artery bypass grafting*

Variable	*Baseline*	*Stabilizer on*	*Ischemia*	*Reperfusion*
FAC (%)	59.9 ± 15.6	61.4 ± 18.1	56.9 ± 17.9†	65.8 ± 15.3‡
LVEDD a-p (mm)	38.4 ± 7.3	35.6 ± 8.7†	37.2 ± 8.2†	37.5 ± 6.9
LVESD a-p (mm)	27.2 ± 7.7	25.2 ± 7.8†	26.8 ± 7.8†	24.8 ± 6.8‡
LVEDD s-l (mm)	38.6 ± 7.5	37.3 ± 7.6†	38.0 ± 7.7	38.1 ± 8.2
LVESD s-l (mm)	28.6 ± 7.5	26.9 ± 8.6†	28.6 ± 9.6†	27.3 ± 8.1
LVEDD apex (mm)	24.6 ± 3.7	21.6 ± 5.1†	24.6 ± 4.2†	25.6 ± 3.4
LVESD apex (mm)	11.2 ± 7.5	10.5 ± 7.8†	14.4 ± 4.9†	10.2 ± 8.3

*Data are shown as the mean ± standard deviation. †*P vs* previous condition; ‡*P vs* baseline; a-p = anterior-posterior plane; s-l = septal-lateral plane; FAC = fractional area change; LVEDD = left ventricular end-diastolic diameter; LVESD = left ventricular end-systolic diameter. *Reprinted with permission from the Society of Thoracic Surgeons (The Annals of Thoracic Surgery 1998; 66: 1084).*

in cardiac index was more important for DIAG revascularization (-14.8 ± 16.8%). Cardiac wall motion and mitral valve function were unaffected even when the heart is displaced at 90 for CX exposure (unpublished data). Also, from our results, changes in LV mitral inflow patterns that could be suggestive of LV diastolic dysfunction[28] were shown to be significant and more important than systolic regional dysfunction (unpublished data). The E/A ratio used to describe such dysfunction was greatly impaired following DIAG and LAD stabilizations (Figure 7). It is inferred that compression of the beating heart for stabilization of the DIAG and LAD prevented normal diastolic expansion by direct deformation of the LV geometry (Figure 6). Such a problem may be prevented by applying minimal compression force on the heart to obtain good exposure, especially when dealing with the DIAG arteries. Other studies using a compression type stabilizer also showed transient hemodynamic changes which recovered after the heart returned to anatomic position.[29,30]

One study evaluated cardiac function during OP-CABG with a compression type stabilizer using invasive hemodynamic and TEE monitoring. In this study, Jurmann *et al.*[31] assessed 28 patients undergoing single bypass grafting to the LAD artery with the internal thoracic artery through a small left anterior thoracotomy. They used the CTS MIDCAB system (Cardiothoracic Systems Inc., Cupertino, CA, USA) and applied gentle pressure until sufficient immobilization of the anastomotic site at the level of the LAD was achieved. They reported that the application of the epicardial stabilizer resulted in a minor decrease in LV end-diastolic and systolic diameter, unchanged fractional area change, while the cardiac index, stroke volume index and pulmonary capillary wedge pressure (PCWP) remained unchanged. After ten minutes of coronary artery occlusion, there was a compromise in LV regional wall motion as represented by the development of new hypokinetic segments or the aggravation of preexisting hypokinetic segments, an increase in LV systolic and diastolic dimension, a decrease in fractional area change (Table II). Diastolic function was not evaluated. In general, this compromise in LV function does not reach critical levels and can easily be compensated through appropriate pharmacologic intervention. The differences, as compared to our results, could be attributed to the operative technique, the use of a different stabilizing device, or a difference in patient populations, as our patients had multivessel disease, with different collateral networks, which are known to affect LV function during vessel occlusion.[22]

Although suction and compression type stabilizers have not been compared directly, the available literature suggests that each type of stabilizer produces a different profile of hemodynamic changes. With the Octopus system, circumflex positioning demonstrated the largest hemodynamic compromise, because the right ventricle is more compressed than the left ventricle, causing a disturbance in diastolic distention.[19] Moreover, with anterior dislocation of the heart, the heart is folded causing a flow obstruction. Contrary to this technique, the verticalization method used at the Montreal Heart Institute does not rely on the dislocation of the heart by the stabilizer. The fan-shape distribution of pericardial stay sutures implanted well below the phrenic nerve line allows reorientation of the apex without manual mobilization of the heart, thus avoiding distortion of the ventricle's geometry.[1] In our series, CX revascularization was associated with a minimal drop in SAP and cardiac index. Likewise, heart stabilization and compression in other territories carried the same decrease in SAP and cardiac index.[25] On the other hand, Jensen *et al.*[18] found minimal hemodynamic effect during revascularization of the anterior and inferior wall using the Octopus stabilizer. Curiously, in our experience, PAP elevations are much more marked when the heart is not vertically displaced during DIAG and LAD revascularization.[25] This is particularly true for patients with severe myocardial dysfunction or with mild to moderate mitral regurgitation. To temporarily obviate this problem, a simple snaring technique of the inferior vena cava had been used[32] with success. This disturbance is thought to be due to the direct compression of the LV outflow tract which leads to abnormal diastolic expansion secondary to direct deformation of the LV geometry.[26] Minimizing compression forces on the heart may prevent these hemodynamic variations.

Value and limitations of monitoring modalities

MONITORING MYOCARDIAL ISCHEMIA

In order to decrease myocardial dysfunction related to each coronary artery territory, our strategy consists of starting with the dominant lesion. This vessel is normally the most collateralized and consequently is less likely to induce myocardial ischemia. We normally avoid bypassing the distal RC artery if the proximal section is not occluded or critically (> 90%) stenotic. Instead, we focus on the posterior descending artery, decreasing the risk of ischemia and arrhythmia, because the atrioventricular artery is bypassed. The circumflex artery is normally revascularized at the end of the procedure.[1]

The common method of intraoperative myocardial ischemia monitoring during CABG is electrocardiography, using the combination of lead II and V5 for ST-segment changes (Figure 8).[33] However, during OP-CABG, the heart is frequently mobilized, particularly for the CX and posterolateral coronary arteries, which often results in microvoltages in the monitored leads. The value of electrocardiography and ST-segment monitoring under these circumstances has not been well explored. TEE is a sensitive method for detecting myocardial ischemia through the observation of segmental wall motion abnormalities during CABG with cardiopulmonary bypass (CPB).[34,35] However, few studies have demonstrated the role of this technique during CABG without CPB. Moisés *et al.* addressed this question in a study evaluating 27 patients undergoing OP-CABG monitored with TEE.[36] Without the use of a stabilizer, they performed a total of 48 anastomoses: 26 to the LAD, three to the DIAG, and 19 to RC. They observed 31 (64%) new segmental wall motion (SWM) abnormalities during coronary occlusion defined as a change in score of 1, as recommended by the American Society of Echocardiography.[27] For each segment, a score was assigned as follows: normal = 1; hypokinetic = 2, akinetic = 3, and dyskinetic = 4. At the time of chest closure, complete recovery occurred in 16 (50%) segments, partial recovery in ten (33%), and no recovery in five (17%). On the seventh postoperative day, the new SWM abnormalities persisted in all five segments without recovery at the end of the surgery and in two of ten (20%) segments with partial recovery. Electrocardiographic ST-segment changes suggestive of myocardial ischemia occurred during only 9/48 (19%) anastomoses confirming its lower sensitivity compared to TEE. In this study, TEE was more predictive of persistent SWM abnormalities in the postoperative period.[36] A study by Kotoh *et al.*[37] uses TEE with colour kinesis to facilitate the evaluation of regional wall motion. Colour kinesis can automatically determine the endocardial excursion by acoustic quantification and demonstrate the change in wall motion in

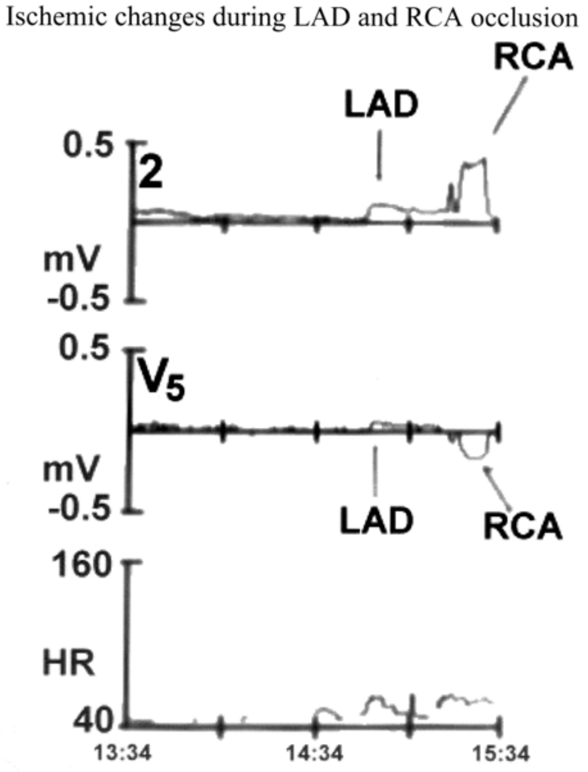

FIGURE 8 Ischemic changes during off-pump bypass cardiac surgery. Significant ST-segment elevations were observed in lead II (top panel) during the left anterior descending (LAD) and right coronary artery (RCA) occlusion. Significant ST-segment elevation occured during LAD occlusion and ST depression during RCA occlusion in lead V5 (middle panel). These ischemic changes were accompanied with an increase in heart rate (HR; lower panel).

colour layers on a single end-systolic frame. From a total of 34 patients undergoing beating heart CABG, they observed new SWM abnormalities in four patients (12%) during the anastomosis of the left internal mammary artery-LAD. Only one of these patients developed electrocardiographic abnormalities. However, electrocardiographic abnormalities were recorded without wall motion abnormalities in three patients. In OP-CABG, the pericardium was displaced to facilitate anastomosis, especially during anastomosis to the CX artery or RC artery. The echocardiographic views of the left ventricle were sometimes limited after pericardial traction during that time. In these cases, TEE may be insufficient to evaluate wall motion suggestive of myocardial ischemia, as is the case for electrocardiography. On the other hand, monitoring of PAP, along with the PCWP has been shown to be insensitive to detect myocardial ischemia in patients undergoing CABG under CPB.[35,38] The use of PCWP as a surrogate is based on the relationship between ischemia and a decrease in ventricular compliance, resulting in an increase in filling pressure as reflected by a rise in PAP and PCWP. van Daele *et al.*[38] found a sensitivity of 33% for an increase in PCWP of 3 mmHg over the baseline to detect myocardial ischemia compared to abnormal wall motion detected by TEE in patients undergoing CABG. All patients with an increase in mean PCWP had inferior wall myocardial ischemia and possible transient papillary muscle dysfunction and mitral valve regurgitation.

Therefore, during OP-CABG, all the monitoring methods have limitations, and we tend to rely on their combination rather than a single mode of monitoring to detect myocardial ischemia. Because most new wall motion abnormalities will resolve within a few minutes after revascularization,[22,36,39] the main interest in intraoperative TEE is after reperfusion. It is well established that detection of persistent SWM abnormalities is associated with postoperative cardiac SWM abnormalities, higher cardiac enzyme levels, and more clinical problems such as pulmonary edema and atrial fibrillation.[36] Such persistent SWM abnormalities after revascularization could lead the surgeon to reevaluate the patency of the coronary bypass graft.

DIAGNOSIS OF HEMODYNAMIC DERANGEMENTS

At the Montreal Heart Institute, patients undergoing OP-CABG are generally monitored with a ST-segment analysis system, a radial artery catheter and a pulmonary artery catheter. The value of continuous cardiac output monitoring in OP-CABG has not been well evaluated. Our experience with TEE during cardiac surgery has been published.[40] TEE has been mainly used for patients with severe myocardial systolic and diastolic dysfunction, mild to moderate mitral regurgitation, or in patients who developed hemodynamic instability during the procedure.

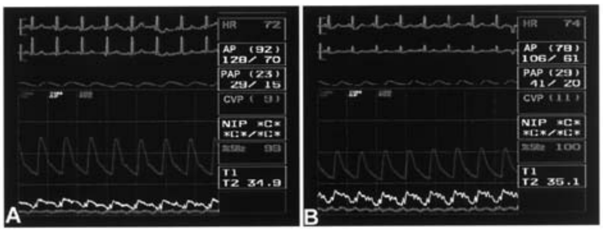

FIGURE 9 A) Effect of removal of the "fork-type" stabilizer positioned over the left anterior descending artery on hemodynamic variables. An increase in systemic blood pressure, a reduction in pulmonary artery pressure and in central venous pressure followed the removal of the stabilizer. B) Off-pump bypass cardiac surgery associated with elevated central venous pressure and pulmonary artery pressure followed by hypotension secondary to compression of the left ventricle during left anterior descending coronary artery anastomosis. This was not associated with any regional wall motion abnormalities but secondary to extracardiac compression.

Hemodynamic instability during OP-CABG can be secondary to ischemia, reduced preload, cardiac compression, myocardial dysfunction, mitral regurgitation, or a combination of these causes.

Myocardial ischemia

As discussed above, all the monitoring methods for myocardial ischemia have limitations. We found TEE most useful in cardiac manipulations during which hypotension is associated with an increased filling pressure (Figure 9). In this situation, TEE can help to differentiate between cardiac dysfunction secondary to myocardial ischemia, in which regional wall motion abnormalities will be present from a much more common scenario where the increase in filling pressure is secondary to extracardiac compression (Dr. A. Denault, personal communication). We found the two-dimensional transesophageal four- and two-chamber view to be the most useful, since the transgastric short axis view is difficult to obtain during OP-CABG, particularly during circumflex and RC artery anastomoses.

Reduced preload

Hypotension secondary to hypovolemia is usually associated with a decrease in PAP and CVP. Fluid loading and Trendelenburg position restores cardiac output by increasing venous hydrostatic pressure and subsequently, LV preload. If these maneuvers are ineffective, we consider the administration of phenyle-

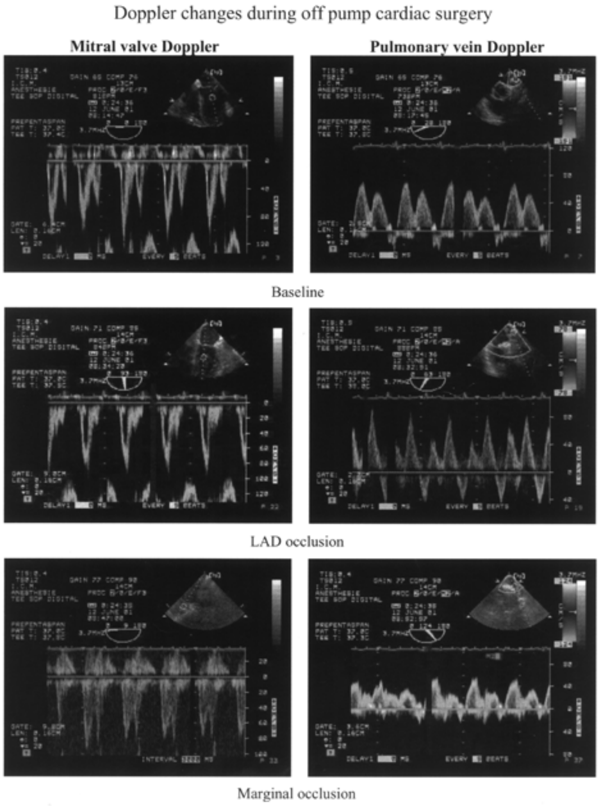

FIGURE 10 Mitral valve and pulmonary vein Doppler inflow during baseline, following left anterior descending (LAD) and marginal artery occlusion. During LAD occlusion, a restrictive pattern appears with a predominant E wave and a reduced S to D wave on the pulmonary vein Doppler signal. The application of the stabilizer probably caused a restrictive pattern because of the compression of the LV. This pattern was rather a relaxation abnormality during marginal occlusion, sometimes observed during myocardial ischemia.

phrine or norepinephrine. TEE can be useful to confirm hypovolemia and fluid responsiveness if the patient remains hypotensive. Using the fork-type stabilizer, exposure of the circumflex and posterior descending arteries necessitates verticalization of the heart, which may occasionally impede atrial preload by distortion of the right atrium and inferior vena cava (Dr. R. Cartier, personal communication).

Myocardial dysfunction

Systolic function

Hemodynamic instability related to severe systolic dysfunction is characterized by an increase in PAP, CVP, along with a decrease in CO. TEE monitoring is

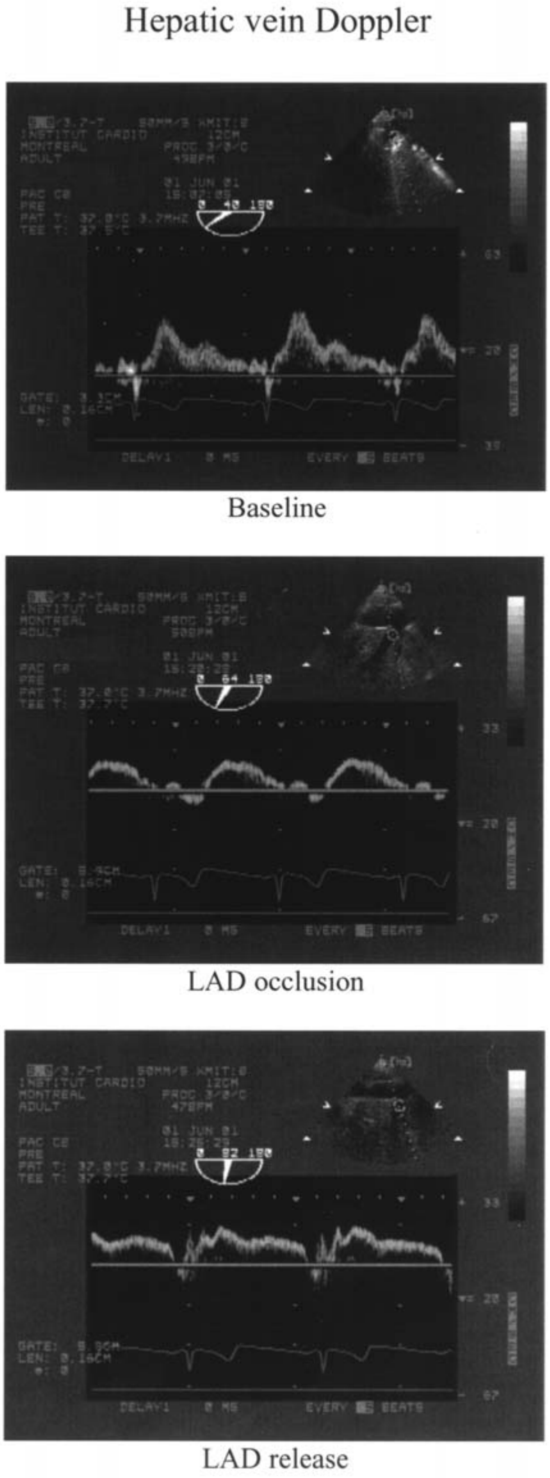

FIGURE 11 Hepatic vein Doppler signal at baseline, following left anterior descending (LAD) occlusion and release. During LAD occlusion, a reversible restrictive pattern on the hepatic vein Doppler signal appears with a reversal of the S wave signal, which suggests a right ventricular compression.

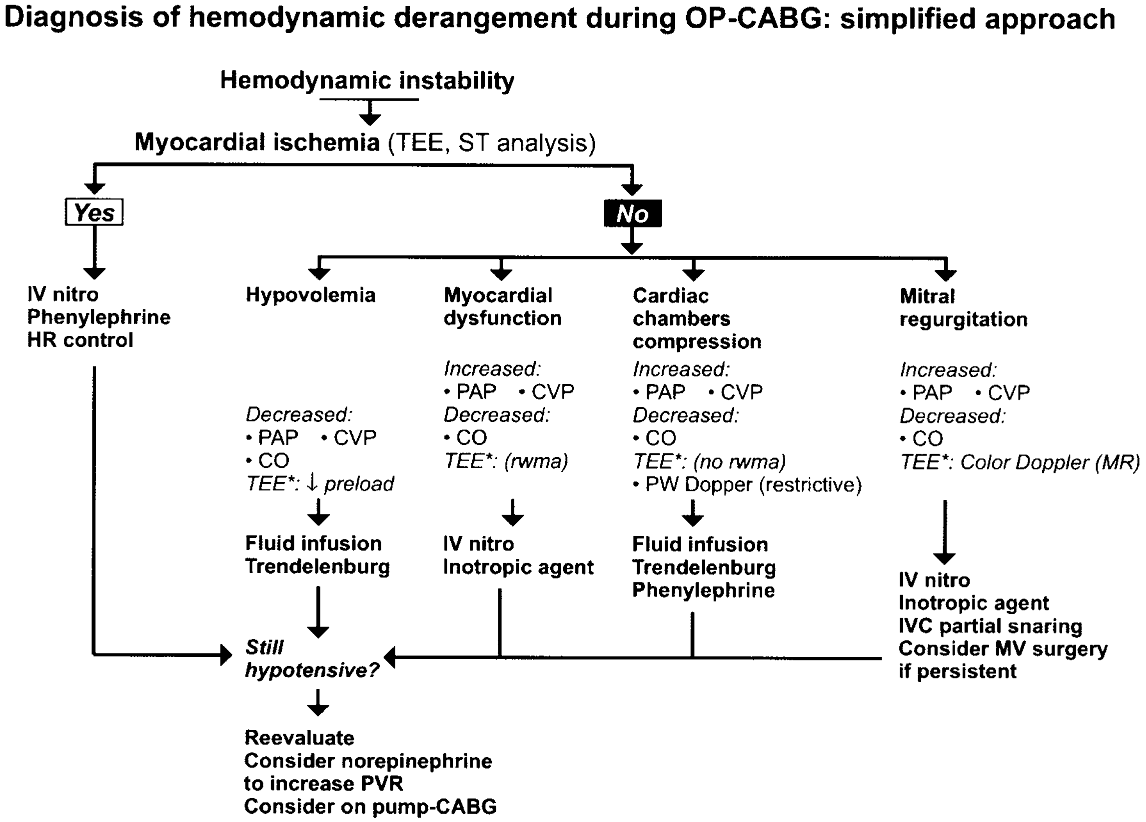

FIGURE 12 *Transesophageal echocardiography (TEE) = evaluation of ventricular dimension with TEE. The left and right ventricle cavity size will be decreased in hypovolemia and compression of the cardiac chambers, and will be increased in myocardial dysfunction and severe mitral regurgitation. TEE is suggested if the patients remain unresponsive to the usual treatment. PAP = pulmonary artery pressure; CVP = central venous pressure; CO = cardiac output; MV Doppler (restrictive) = restrictive pattern of the mitral valve inflow measured with pulsed Doppler; colour Doppler (MR) = mitral regurgitation as evaluated with colour Doppler; IV nitro = *iv* nitroglycerine; IVC snaring = snaring of the inferior vena cava to control pulmonary hypertension; HR = heart rate; PVR: peripheral vascular resistance.

particularly useful to differentiate between systolic dysfunction associated with regional wall motion abnormalities from cardiac compression where the increase in filling pressure is secondary to extracardiac compression (Dr. A. Denault, personal communication). TEE may be considered in patients with known preoperative systolic dysfunction, or in patients who remain hypotensive despite *iv* nitroglycerine and inotropic support.

Diastolic dysfunction

Our group has recently raised the issue of the importance of diastolic function evaluation during cardiac surgery.[41] The role of diastolic function evaluation during OP-CABG surgery is not reported in the literature. We are currently using Doppler to evaluate both left (Figure 10) and right diastolic function (Figure 11) during OP-CABG. Such an evaluation allows us to better understand the hemodynamic changes occurring during this procedure, but remains an investigative tool.

Cardiac compression

During anterior descending and DIAG artery positioning with the compression type stabilizer, minimal pressure is applied by the stabilization device to avoid direct compression of the LV outflow tract leading to abnormal diastolic expansion. This may lead to an increase in PAP and CVP. Using the Octopus stabilizer, the main causes of hemodynamic disturbance during positioning are thought to be decreased RV filling, and to a lesser extent, LV filling, by direct ventricular compression. Volume loading, Trendelenburg position, and vasopressor infusion usually correct these derangements, although the RV assist device has been proposed for unstable patients.[19] TEE is indicated in patients who are not responsive to the above treatment and helps to differentiate between cardiac dysfunction and extracardiac compression.

Mitral regurgitation

In occasional cases, significant acute mitral valve dysfunction can precipitate hemodynamic instability following heart positioning or coronary artery clamping. Patients who are most at risk to develop severe mitral valve regurgitation are those with preexisting myocardial dysfunction or mild to moderate mitral regurgitation (Dr. R. Cartier, personal communication). When increases of PAP and CVP are observed, colour Doppler TEE of the mitral valve can make the diagnosis. In these cases, we administer *iv* nitroglycerin and inotropic agents. Inferior vena cava clamping has been used to control an acute increase in PAP unresponsive to usual treatment.[32] Mitral valve repair or replacement can be considered if persistent after revascularization, and thus will lead to cancellation of the OP-CABG.

Figure 12 summarizes our approach to diagnose hemodynamic derangement during OP-CABG.

Conclusion

In summary, hemodynamic changes secondary to the stabilization technique or transient ischemia represent an important diagnostic challenge during OP-CABG. The mechanism can vary according to the stabilization system. Current monitoring such as ECG and hemodynamic monitoring are used but their usefulness in establishing the mechanism of hemodynamic instability remains limited. In our experience, TEE is used in selected patients, particularly those with severe myocardial systolic and diastolic dysfunction, mild to moderate mitral regurgitation, or for patients who are unstable during the procedure.

Conflict of interest statement

Dr. Raymond Cartier has a consultantship agreement with CoroNéo Inc.

References

1 *Cartier R, Blain R.* Off-pump revascularization of the circumflex artery: technical aspect and short-term results. Ann Thorac Surg 1999; 68: 94–9.
2 *Bell MR, Gersh BJ, Schaff HV, et al.* Effect of completeness of revascularization on long-term outcome of patients with three-vessel disease undergoing coronary artery bypass surgery. A report from the Coronary Artery Surgery Study (CASS) Registry. Circulation 1992; 86: 446–57.
3 *Gundry SR, Romano MA, Shattuck OH, Razzouk AJ, Bailey LL.* Seven-year follow-up of coronary artery bypasses performed with and without cardiopulmonary bypass. J Thorac Cardiovasc Surg 1998; 115: 1273–7.
4 *Tasdemir O, Vural KM, Karagoz H, Bayazit K.* Coronary artery bypass grafting on the beating heart without the use of extracorporeal circulation: review of 2052 cases. J Thorac Cardiovasc Surg 1998; 116: 68–73.
5 *Benetti FJ, Naselli G, Wood M, Geffner L.* Direct myocardial revascularization without extracorporeal circulation. Experience in 700 patients. Chest 1991; 100: 312–6.
6 *Shennib H, Mack MJ, Lee AG.* A survey on minimally invasive coronary artery bypass grafting. Ann Thorac Surg 1997; 64: 110–4.
7 *Cartier R, Hébert Y, Blain R, Tremblay N, Desjardins J, Leclerc Y.* Triple coronary artery revascularization on the stabilized beating heart: initial experience. Can J Surg 1998; 41: 283–8.
8 *Dagenais F, Perrault LP, Cartier R, et al.* Beating heart coronary artery bypass grafting: technical aspects and results in 200 patients. Can J Cardiol 1999; 15: 867–72.
9 *Cartier R.* From idea to operating room: surgical innovation, clinical application, and outcome. Seminar in Cardiothoracic and Vascular Anesthesia 2000; 4: 103–9.
10 *Borst C, Jansen EW, Tulleken CAF, et al.* Coronary artery bypass grafting without cardiopulmonary bypass and without interruption of native coronary flow using a novel anastomosis site restraining device (“Octopus”). J Am Coll Cardiol 1996; 27: 1356–64.
11 *Grundeman PF, Borst C, van Herwaarden JA, Mansvelt Beck HJ, Jansen EWL.* Hemodynamic changes during displacement of the beating heart by the Utrecht Octopus method. Ann Thorac Surg 1997; 63: S88–S92.
12 *Jansen EW, Grundeman PF, Mansvelt Beck HJ, Heijmen RH, Borst C.* Experimental off-pump grafting of a circumflex branch via sternotomy using a suction device. Ann Thorac Surg 1997; 63(Suppl 6): S93–S6.
13 *Grundeman PF, Borst C, van Herwaarden JA, Verlaan CWJ, Jansen EWL.* Vertical displacement of the beating heart by the Octopus tissue stabilizer: influence on coronary flow. Ann Thorac Surg 1998; 65: 1348–52.
14 *Grundeman PF, Borst C, Verlaan CWJ, Meijburg H, Moues CM, Jansen EWL.* Exposure of circumflex branches in the tilted, beating porcine heart: echocar-

diographic evidence of right ventricular deformation and the effect of right or left heart bypass. J Thorac Cardiovasc Surg 1999; 118: 316–23.

15 *Porat E, Sharony R, Ivry S, et al.* Hemodynamic changes and right heart support during vertical displacement of the beating heart. Ann Thorac Surg 2000; 69: 1188–91.

16 *Spooner TH, Dyrud PE, Monson BK, Dixon GE, Robinson LD.* Coronary artery bypass on the beating heart with the Octopus: a North American experience. Ann Thorac Surg 1998; 66: 1032–5.

17 *Nierich AP, Diephuis J, Jansen EW, Borst C, Knape JT.* Heart displacement during off-pump CABG: how well is it tolerated? Ann Thorac Surg 2000; 70: 466–72.

18 *Jansen EWL, Borst C, Lahpor JR, et al.* Coronary artery bypass grafting without cardiopulmonary bypass using the Octopus method: results in the first one hundred patients. J Thorac Cardiovasc Surg 1998; 116: 60–7.

19 *Mathison M, Edgerton JR, Horswell JL, Akin JJ, Mack MJ.* Analysis of hemodynamic changes during beating heart surgical procedures. Ann Thorac Surg 2000; 70: 1355–61.

20 *Mathison M, Buffolo E, Jatene AD, et al.* Right heart circulatory support facilitates coronary artery bypass without cardiopulmonary bypass. Ann Thorac Surg 2000; 70: 1083–5.

21 *Lönn U, Peterzén B, Carnstam B, Casimir-Ahn H.* Beating heart coronary surgery supported by an axial blood flow pump. Ann Thorac Surg 1999; 67: 99–104.

22 *Koh TW, Carr-White GS, DeSouza AC, Ferdinand FD, Pepper JR, Gibson DG.* Effect of coronary occlusion on left ventricular function with and without collateral supply during beating heart coronary artery surgery. Heart 1999; 81: 285–91.

23 *Brown PM Jr, Kim VB, Boyer BJ, Lust RM, Chitwood WR Jr, Elbeery JR.* Regional left ventricular systolic function in humans during off-pump coronary bypass surgery. Circulation 1999; 100(Suppl II): II-125–II-7.

24 *Eldrup N, Rasmussen NH, Yndgaard S, Biggler D, Berthelsen PG.* Impact of off-pump coronary artery surgery on myocardial performance and ß-adrenoceptor function. J Cardiothorac Vasc Anesth 2001; 15: 428–32.

25 *Do QB, Cartier R.* Hemodynamic changes during bypass surgeries in the beating heart. Ann Chir 1999; 53: 706–11.

26 *Do QB, Chavanon O, Couture P, Denault A, Cartier R.* Hemodynamic repercussion during beating-heart CABG surgery. Can J Cardiol 1999; 15(Suppl D): 177D (abstract).

27 *Schiller NB, Shah PM, Crawford M, et al.* Recommendations for quantitation of the left ventricle by two- dimensional echocardiography. American Society of Echocardiography Committee on Standards, Subcommittee on Quantitation of Two-Dimensional Echocardiograms. J Am Soc Echocardiogr 1989; 2: 358–67.

28 *Rakowski H, Appleton C, Chan KL, et al.* Canadian consensus recommendations for the measurement and reporting of diastolic dysfunction by echocardiography: from the Investigators of Consensus on Diastolic Dysfunction by Echocardiography. J Am Soc Echocardiogr 1996; 9: 736–60.

29 *Watters MPR, Ascione R, Ryder IG, Ciulli F, Pitsis AA, Angelini GD.* Haemodynamic changes during beating heart coronary surgery with the 'Bristol technique'. Eur J Cardiothorac Surg 2001; 19: 34–40.

30 *Burfeind WR Jr, Duhaylongsod FG, Samuelson D, Leone BJ.* The effects of mechanical cardiac stabilization on left ventricular performance. Eur J Cardiothorac Surg 1998; 14: 285–9.

31 *Jurmann MJ, Menon AK, Haeberle L, Salehi-Gilani S, Ziemer G.* Left ventricular geometry and cardiac function during minimally invasive coronary artery bypass grafting. Ann Thorac Surg 1998; 66: 1082–6.

32 *Dagenais F, Cartier R.* Pulmonary hypertension during beating heart coronary surgery: intermittent inferior vena cava snaring. Ann Thorac Surg 1999; 68: 1094–5.

33 *London MJ, Hollenberg M, Wong MG, et al.* Intraoperative myocardial ischemia: localization by continuous 12-lead electrocardiography. Anesthesiology 1988; 69: 232–41.

34 *Smith JS, Cahalan MK, Benefiel DJ, et al.* Intraoperative detection of myocardial ischemia in high-risk patients: electrocardiography versus two-dimensional transesophageal echocardiography. Circulation 1985; 72: 1015–21.

35 *Leung JM, O'Kelly B, Browner WS, Tubau J, Hollenberg M, Mangano DT.* Prognostic importance of postbypass regional wall-motion abnormalities in patients undergoing coronary artery bypass graft surgery. McSPI Research Group. Anesthesiology 1989; 71: 16–25.

36 *Moisés VA, Mesquita CB, Campos O, et al.* Importance of intraoperative transesophageal echocardiography during coronary artery surgery without cardiopulmonary bypass. J Am Soc Echocardiogr 1998; 11: 1139–44.

37 *Kotoh K, Watanabe G, Ueyama M, et al.* On-line assessment of regional ventricular wall motion by transesophageal echocardiography with color kinesis during minimally invasive coronary artery bypass grafting. J Thorac Cardiovasc Surg 1999; 117: 912–7.

38 *van Daele ME, Sutherland GR, Mitchell MM, et al.* Do changes in pulmonary capillary wedge pressure adequately reflect myocardial ischemia during anesthesia?

A correlative preoperative hemodynamic, electrocardiographic, and transesophageal echocardiographic study. Circulation 1990; 81: 865–71.

39 *Malkowski MJ, Kramer CM, Parvizi ST, et al.* Transient ischemia does not limit subsequent ischemic regional dysfunction in humans: a transesophageal echocardiographic study during minimally invasive coronary artery bypass surgery. J Am Coll Cardiol 1998; 31: 1035–9.

40 *Couture P, Denault AY, McKenty S, et al.* Impact of routine use of intraoperative transesophageal echocardiography during cardiac surgery. Can J Anesth 2000; 47: 20–6.

41 *Bernard F, Denault A, Babin D, et al.* Diastolic dysfunction is predictive of difficult weaning from cardiopulmonary bypass. Anesth Analg 2001; 92: 291–8.

Rocky Mountains